GASIFICATION OF RUBBERWOOD IN A DOWNDRAFT GASIFIER

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Doctor of Philosophy

THE UNIVERSITY OF ASTON IN BIRMINGHAM

JUNE 1991

The University of Aston in Birmingham

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SUMMARY

The objectives of this research were to investigate the performance of a rubberwood gasifier and engine with electricity generation and to identify opportunities for the implementation of such a system in Malaysia.

The experimental work included the design, fabrication and commissioning of a throated downdraft gasifier in Malaysia. The gasifier was subsequently used to investigate the effect of moisture content, dry wood capacity and particle size of rubberwood on gasifier performance. Additional experiments were also conducted to investigate the influence of two different nozzle numbers and two different throat diameters on tar cracking.

A total of 101 runs were completed which were achieved with good mass and energy balance closures. The overall gasifier eficiency from wood to cold clean gas averaged 47.5% and the conversion efficiency to electrical power averaged 17.8%.

It was found that wood with moisture content of up to 51.5% (wet basis) was sucessfully gasified. It was also found that the gasifier was able to handle at least 1.5 times its design capacity. The maximum throughput for stable operation was found to be 60-70% of the maximum dry wood capacity.

The gasifier was found to have a maximum turndown ratio of 5:1. It is also postulated that the phenomenon of turndown of the gasifier is due to a "bubble theory" occurring at the gasification zone, and this hypothesis is explained.

The research also showed that rubberwood gasification in Malaysia is feasible if the price of diesel is above MR$35/l and the price of wood is below MR$120/tonne.

Key Words : Malaysia, rubberwood, downdraft gasifier, throated, mass and energy balances, heat losses and turndown, bubble theory.

ACKNOWLEDGEMENTS

The author would like to thank Dr. Tony Bridgwater for his supervision of this work in which he has shown great interest and provided very valuable inputs into the research and the preparation of this thesis.

The author would also like to thank the following persons for making this research work and thesis possible,

The two other associate supervisors, Dr. Eric Smith and Dr. Abdul Razak Mohd. Ali for their very valuable assistance and advice during the research and the preparation of the thesis.

Dato' Dr.Salleh Mohd. Nor, Director-General of Forest Research Institute of Malaysia for his support of the project.

Dr. Azizol Abdul Kadir, Director of Chemistry, Forest Research Institute of Malaysia for making available all the facilities for carrying out the research.

My wife Bee Yan for her encouragement and inspiration, sons James and Jeffrey for the their patience and understanding for their lack of holidays with the author throughout the three years of research.

Mr. Andrew Wong for helping the author in proof reading the thesis.

Mr. Harry Cheah for making all the arrangements with my sponsors during my stay in England.

Mr. Khoo Kean Choon and Dr. Koh Mok Poh for their general assistance during the research.

All the members of the "A" team for their analysis work and general assistance.

All members of the Energy Research Group, Aston University, for their kind assistance during the writing-up of the thesis. Particular thanks go to Mr. Cordner Peacocke who assisted the author in preparation of the drawings in Chapter 5.

The author also wishes to express his gratitude to United Nations Development Programme for their financial support by way of a Fellowship. Gratitude is also expressed to Rubber Research Institute Malaysia, Universiti Kebangsaan Malaysia, Universiti Teknologi Malaysia, Jabatan Alam Sekitar Malaysia for permission to use their facilities during the research.

Last and perhaps more importantly, I would like to thank God for giving me all the strength to complete this research.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Malaysia is the world's leading producer of natural rubber, a commodity produced from the rubber tree (*Hevea brasiliensis*). In 1988, Malaysia's natural rubber export accounted for 33.1% of the total world natural rubber production (Table 1.1). Natural rubber was the third largest revenue earner for the country in 1988 (Anon, 1990a).

Table 1.1
Natural rubber producing countries

Country	Tonnes	% world production
Malaysia	1 660 300	33.1
Indonesia	1 235 000	24.6
Thailand	974 900	19.4
Sri Lanka	122 400	2.4
India	254 800	5.1
Others	773 170	15.4
Total	**5 020 570**	**100.0**

(Association of Natural Rubber Producing Countries, 1989)

The economic lifetime of rubber trees is 25-30 years, at the end of which they are felled to make way for replanting. The total quantity of rubberwood produced annually from the felling of old rubber trees is estimated to be about 33.021 million tonnes per year in Peninsular Malaysia. The main uses of rubberwood are as follows:

a) Fuel for kiln drying of timber, rubber smoking, tobacco curing and brick making.
b) Charcoal production for the steel industry.
c) Production of other value added products such as particle-board, cement board and furniture.

In 1988, the total quantity of rubberwood consumed by the above industries amounted to about 4.114 million tonnes per annum leaving 28.907 million tonnes as residues. These wastes have to be disposed of, often by burning in the open and causing air pollution (Hoi, 1985). Norini et al. (1990) projected the net total quantity of rubberwood to be processed into timber and other value added by-products is expected to increase in the future. Although the recovery process of rubberwood is also expected to improve due to better technological development, the quantity of rubberwood residues in many different forms generated by downstream operation is also projected to be very substantial in the future.

During the oil shortage of the nineteen seventies, a number of manufacturing sectors within the wood-based industries encountered the problem of increased fuel cost and uncertainty of supplies of fossil fuels for energy. It was soon realised that the petroleum based fuels cannot be depended on for too long and alternative sources of energy would have to be found to generate energy for the wood-based industries.

One of the alternatives is to derive energy from wood residues generated by the wood-based industries. One of the main source of wood residues is rubberwood. Although rubberwood has long been used as fuel, it is either used in its raw form as fuelwood for domestic consumption and as processed heat for timber drying or in the form of charcoal (Hoi, 1985). Although these technologies are relatively well established, applications are limited to the production of steam for timber drying or process heat. No published information and research have been found on the enhancement of rubberwood utilisation by converting it into different forms of energy such as liquid or gaseous fuels.

Thermochemical conversion of biomass such as wood offers a versatile range of methods for producing almost any fuel products through the process of gasification, combustion, pyrolysis and liquefaction. Of the different thermochemical processes, gasification is considered to be the most versatile, based on the present state of development and the number of applications (Bridgwater et al., 1986). This process widens the market for biomass derived fuels by producing clean gas fuels which can be used to generate electricity in internal combustion engines. Although biomass

gasification technology has been widely used since the Second World War, it has undergone many improvements and development (Kaupp and Goss, 1981). In fact small scale units are commercially available and in use in Brazil, Thailand, Philippines and many other developing countries. The main applications of gasification are in the form of process heat for drying or retrofitted to engines for the generation of electricity or shaft power particularly in rural areas (Bridgwater et al., 1986; Kjellstrom, 1989).

1.2 OBJECTIVES

The increasing quantities of rubberwood residues and the growing global concern about pollution and the environment offer incentives to find a solution to more efficient disposal or utilisation of these residues. Within the context of concern over energy resources and the environment, a significant contribution could be derived from the conversion of rubberwood into a more economically sound heat production and power generation system through gasification. Thus the primary objectives of this research are:

1. design and build a gasifier fuelled with rubberwood.
2. study the gasification characteristics of rubberwood.
3. evaluate the performance of the gasifier and total system through mass and energy balance determinations.
4. acquire practical experience of operating a gasifier/engine generating set system for Malaysia.
5. identify opportunities for implementation of such a system in Malaysia.

Although the main emphasis of this work is on the gasification of rubberwood, other areas of investigation such as the assessment of the potential of such a system in Malaysia in terms of resource availability and the overall and specific energy needs of the country have also been carried out.

CHAPTER 2

ENERGY RESOURCES IN MALAYSIA

2.1 INTRODUCTION

More than a century ago, energy needs in Malaysia were largely met by non-commercial sources such as firewood and agricultural residues. The subsequent discovery and mining of coal led to the commercial application of coal in power generation and rail transport. The discovery of oil, natural gas and the development of hydro power for electricity generation further displaced the non-commercial energy sources. Today, Malaysia's energy supply and demand is based on oil, natural gas, hydroelectricity, fuelwood and coal. The significance, locations and utilisation of these energy resources are presented in this chapter.

2.2 OIL

Oil emerged as an important source of commercial energy in Malaysia with the establishment of the Lutong refinery in Sarawak in 1917 and the subsequent development of a petroleum industry. As the refineries at Port Dickson and other locations in the region came on-stream in the early 1960's, oil began to play a progressively greater role in the Malaysian energy scenario, displacing coal as well as other non-commercial sources of energy in the country (Gumm, 1985). Malaysia's proven crude oil reserves amount to approximately 16 800 PJ , distributed as shown in Table 2.1.

Table 2.1
Recoverable reserves of oil in Malaysia (PJ)*
(Petronas, 1990)

Peninsular Malaysia	8042
Sarawak	5563
Sabah	3195
Total	**16800**

* 41.84 PJ = 10^6 tonne of oil equivalent (toe)

Oil resources are mainly located at off-shore areas in three main groups of fields, namely off the east coast of Trengganu and the north coast of Sabah and Sarawak. Malaysian crude is light with a low sulphur content and is mainly exported because of its higher premium in international markets. Almost 80% of Malaysian energy demand is however met by cheaper heavier crude which is imported from the Middle East. While Malaysia is in a fortunate position in terms of financial revenues derived from this fuel, there is however a general awareness that the current reserves are finite and could be exhausted within the next 15 years based on the current rate of oil exploration (Chooi, 1989; Hamzah, 1990).

2.3 NATURAL GAS

In terms of energy, Malaysia has a larger reserve of natural gas than oil. The natural gas resources fall into two categories:

a) associated gas, which is found in oil fields, and is therefore released when crude oil is produced.

b) non-associated gas, which occurs in gas fields and is therefore not associated with crude oil.

Associated gas reserves are in the region of 12334 PJ. As is common practice in most countries, all of the associated gas produced in the country is flared or vented because it is not competitive to utilise the gas in the local market due to high cost of transporting the gas to the utilisation centres.

In contrast, Malaysia's non-associated gas reserves are in the region of 48466 PJ, of which about 24007 PJ are located off the east coast of Peninsular Malaysia and the remaining 24459 PJ are located off Sabah and Sarawak. The quantity of non-associated gas reserves in energy terms is about three times larger than that of recoverable oil reserves in the country (see section 2.2).

The quantity of associated and non-associated gas in Malaysia for 1988 is summarised in Table 2.2 .

Table 2.2
Recoverable reserves of gas in Malaysia (PJ)

	Associated	Non-Associated	Total
Peninsular Malaysia	6 631	24 007	30 638
Sarawak	4 463	22 917	27 380
Sabah	1 240	1 542	2 782
Total	**12 334**	**48 466**	**60 800**

Of the total quantity of natural gas produced in 1988, about 63.6 % of it was used for the production of liquefied natural gas or LNG for export. The remaining 36.4% was utilised for the local gas-based industries (Anon, 1990a).

In view of the large resource base of natural gas, it has been government policy over the last 5 years to concentrate on developing a more widespread use of natural gas (Anon, 1987). For example, several large gas based projects in the country have been undertaken over the past 5 years, and some of the major gas based projects undertaken are summarised in Table 2.3.

Table 2.3
Major existing gas projects in Malaysia
(Petronas, 1990)

Projects	Gas consumption (PJ/day)
Paka power plant	0.162
Perwaja Steel mill	0.027
LNG	1.449
Ammonia/Urea production	0.058
Methanol	0.064
Sponge iron	0.023

2.4 HYDRO POWER

Malaysia has a technical hydropower potential of about 440 PJ/y. This represents a very strong resource base and is equivalent to 63.5% of the

total commercial energy supply in Malaysia in 1988 (see Table 2.6). However, the location of hydropower resources does not always correspond to energy demand centres. In fact, only 13% of the total technical hydro potential exists in Peninsular Malaysia where about 82% of the total population resides. However, Sarawak, with only 9% of the population, accounted for almost 71% of the total hydro potential (Hoesni, 1985). In 1988, 16.7 PJ/y was generated from existing or on-going hydro projects in Peninsular Malaysia while another 3.2 PJ/y and 0.7 PJ/y were available in Sarawak and Sabah respectively. The total and exploited hydro potential is summarised in Table 2.4.

Table 2.4
Hydroelectric power potential in Malaysia (PJ/y)
(Anon, 1990a)

	Technical potential	Current usage
Peninsular Malaysia	57.2	16.7
Sarawak	311.2	3.2
Sabah	71.6	0.7
Total	**440.0**	**20.6**

2.5 FUELWOOD

Fuelwood resources are mainly from the by-products of the forestry and the rubber industries. Although there is no reliable data on the actual use of fuelwood, it is the principal source of energy to a large number of industries in the rural areas of Malaysia such as the tobacco, rubber, charcoal, kiln drying and brick industries (Hoi, 1985; Hoi et al., 1990; 1991). The use of fuelwood in these industries will be discussed in chapter 3. The overall fuelwood resource in the country is estimated to be in the region of 500 PJ/y, equivalent to the hydro potential in the country (Baharudin and Hoi, 1987; Anon, 1988; Tan et al., 1981).

2.6 COAL

Malaysia has a history of coal mining that dates back to 1847 when coal was first mined in the island of Labuan. Coal mining in Peninsular Malaysia however, only started in 1908 with the Batu Arang mine. The quantities

mined were relatively small and it was estimated that when production ceased in 1960, the total amount of coal mined was only 18 million tonnes. At present, Malaysia's coal resources are all located in Sarawak. Estimates of technical recoverable coal reserves is 15250 PJ (Anon, 1988). The amount of coal exploited in 1988 was 550 PJ (Anon, 1988).

In spite of the embryonic nature of coal exploration efforts in the country, it has been the policy of the government to develop coal as an important fuel of the future (KTTP, 1986). It is anticipated that most of the coal resource will have to be imported from neighbouring countries within the Asian-Pacific region until coal from Sarawak can be exploited on a larger commercial scale. Despite the potential dependancy on coal from foreign sources, the government is convinced that imported coal will still be a competitive source of energy in the country (Zamzam, 1990). As an initial step, all new cement plants in Malaysia will be required to be based on coal. A major coal fired power station in Port Kelang is under construction to supply power to the Klang Valley.

2.7 SUMMARY

The energy resource base of the country is summarised in Table 2.5.

Table 2.5
Energy resources in Malaysia

Source	Currently verified reserves (PJ)	%
Oil	16 800	12.0
Gas	60 800	43.5
Hydro (for 50 year life-span)	22 000	15.7
Coal	15 250	10.9
Fuelwood (for 50 year rotation)	25 000	17.9
Total	**139 850**	**100.0**

2.8 COMMERCIAL ENERGY PRODUCTION IN 1988

The commercial energy supply for the country in 1988 is summarised in Table 2.6.

Table 2.6
Commercial energy supply in Malaysia,1988

Source	Amount (PJ)	%
Heavy fuel oil products	320	46.2
Gas	195	28.1
Light petroleum products	109	15.7
Coal	11	1.6
Electricity	54	7.8
Fuelwood	4	0.6
Total	**693**	**100.0**

The primary energy mix in 1988 clearly showed the dominant role of oil, gas and other petroleum products. Due to the limited reserve of oil in the country, the high dependence on oil had clearly been identified as an issue of concern. The government had in 1985 instituted a four-fuel policy aimed at reducing the heavy dependence on oil and to encourage a better diversification the national primary energy resource (KTTP, 1986). In the policy, hydro, coal and biomass energy have been identified for further development in the future primarily due to their relatively large resource base.shown in Table 2.5.

2.9 COMMERCIAL ENERGY DEMAND IN 1988

Table 2.7 shows the final energy demand by sector in Malaysia for 1988.

Table 2.7
Final energy demand by sector, 1988

Sector	Quantity (PJ)	%
Residential and Commercial	60	13.6
Industrial	183	41.5
Transport	183	41.5
Non energy uses	15	3.4
Total	**441**	**100.0**

As expected the transport and industrial sector were the major consumers of energy. Over the long term, the share of the industrial sector is expected to grow faster than the transport sector in view of the strong emphasis placed by the government on industrialisation and the development of heavy industries in the country. The residential and commercial sector and the non energy sector are expected to remain at about the same level in the next few years.

2.10 CONCLUSION

In conclusion, it is shown that in addition to oil and gas, Malaysia also has a large energy resource of hydro, coal and wood. Although these indigenous resources constitute almost 44.5 % of the total energy resource base in the country, it was shown they only contributed to 10% of the total commercial energy supply in 1988.

In 1988, it was concluded that 90% of the commercial energy were derived from oil and gas. Due to the limited supply, the heavy dependence on oil has been identified as an issue of concern particularly if no additional oil fields are found. In the immediate future, the major source of energy is expected to be from natural gas. Over the recent years, great deal of attention has been directed towards developing a fuller utilisation of this resource. However, like oil, the government is aware that the gas resource is finite and can be depleted if the utilisation rate is not managed properly.

To reduce the over dependence on oil, the government has, in recent years, drawn up a number of policies (such as the four fuel diversification policy) which are aimed at the development of efficient utilisation of other indigenous resources such as hydro and biomass. The successful development of these energy resources will help to provide the nation with additional sources of energy for her industrial development.

CHAPTER 3

ASSESSMENT OF RUBBERWOOD RESIDUES IN MALAYSIA

3.1 INTRODUCTION

The total land area in Malaysia is estimated to be 32.90 million hectares (ha). The land area under natural forest in Malaysia is estimated to be 20.10 million ha (or 61.1 % of the total land area) while plantation crops grown on agricultural land occupy 4.89 million ha (or 14.9 % of the total land area). The plantation crops grown in 1988 are summarised in Table 3.1 (Anon 1990).

Table 3.1
Total area of plantation crops grown in Malaysia, 1988

Crops	Area (10^6 ha)	%
Rubber	1.94	39.67
Oil Palm	1.69	34.56
Cocoa	0.33	6.75
Paddy	0.62	12.68
Coconut	0.31	6.34
Total	**4.89**	**100.00**

One of the major characteristics of the forestry and agricultural sector (from which plantation crops are grown) is the production of large quantities of processing residues which have no economic value (Jalaludin et al., 1984). Their presence in recent years posed a major disposal problem now that burning is being actively discouraged by the regulatory agencies (Department of Environment of Malaysia, 1987 ; 1988).

Rubberwood residues that are generated from rubbertrees have been identified as both a major resource and major problem because of the relatively large area on which they are cultivated (see Table 3.1). At present, there is no reliable statistical data on the actual quantity of rubberwood residues available in the country. This chapter attempts to quantify as accurately as possible, the annual amount of rubberwood residues generated during replanting programmes and to identify the main

users of these residues. From the supply-demand data, an assessment of an annual quantity of surplus rubberwood residues in Malaysia can be made.

3.2 RUBBERWOOD

Theoretically, the economic lifetime of a rubber tree is generally taken as 25 -30 years but in practice they are never replanted before 30 years (Ani and Ariffin, 1981). On an average, about 3-4 % of the total rubberwood plantation area is replanted each year (Harris, 1979; RRIM, 1988). At the end of its economic life, the rubber tree has an average height of about 18 m and an average diameter of about 0.7 m at breast height level. The average weight of a representative rubber tree (together with the leaves, branches, stem, roots, etc) has been estimated to be 3591 kg on a dry basis (RRIM, 1988). The breakdown of the various constituents are given in Table 3.2.

Table 3.2
Composition of a typical rubber tree at the end of its economic life (RRIM, 1988)

Fractions	Total dry weight per tree kg	%	Total weight/ha tonne*
Leaves	67	1.8	13.4
Leaf-stalks	9	0.3	1.8
Twigs	105	2.9	21.0
Branches	1 831	51.0	366.2
Main stem**	1 032	28.8	206.4
Roots	547	15.2	109.4
Total	**3 591**	**100.0**	**718.2**

* Assuming an average of 200 trees/ha
** logs with diameter of 15 cm and above

3.3 AVAILABILITY OF RUBBERWOOD DURING REPLANTING

The total area of mature rubber plantation was obtained from planting data obtained from 1958-1970 (Anon, 1990). Planting data from 1970-1990, are however, not available due to restricted disclosure of the Malaysian

Government on rubberwood. Taking a replanting of 30 years, the total areas of mature rubber plantations in 1988-2000 is estimated in Table 3.3.

Table 3.3
Total mature areas of rubber plantations, 1988-2000

Year of planting	Expected year of replanting	Mature area for replanting (10^3 ha)
1958	1988	58.12
1959	1989	58.12
1960	1990	58.12
1961	1991	89.97
1962	1992	94.28
1963	1993	105.68
1964	1994	86.67
1965	1995	81.57
1966	1996	54.14
1977	1997	52.94
1968	1998	25.83
1969	1999	33.63
1970	2000	49.94

3.4 ASSESSMENT OF RUBBERWOOD RESIDUES FOR GASIFICATION

During the replanting process, not all the rubberwood is extracted. A large proportion of the biomass is left behind in the field to be burnt away later. In order to assess the total quantity of usable rubberwood residues (for example as gasification fuels), it is necessary to quantify both the amount of usable rubberwood residues left behind and also residues derived from the logs that are extracted for primary and secondary processing.

3.4.1 Sources of rubberwood residues left behind during replanting

Gan et al., (1985) estimated that an average 14 % or 100.5 t/ha of usable larger diameter logs (above 15 cm in diameter) is extracted for further processing. By extracting 100.5 t/ha of wood, the quantity of rubberwood residues left behind is, therefore, about 617.7 t/ha (see Table 3.2). However, not all residues left behind are usable. The leaves, leaf-stalks, twigs and roots are not usable residues due to the nature, physical form and

soil contamination of the residues. The total quantity of usable rubberwood residues during replanting is summarised in Table 3.4.

Table 3.4
Total quantity of usable rubberwood residues available during replanting

Source		Tonne/ha
Total rubberwood resource		718.2
Logs extracted		100.5
Total rubber residues left behind		617.7
Not usable residues		
Leaves	13.4	
Leaf-stalks	1.8	
Twigs	21.0	
Roots	109.4	
Total	145.6	145.6
Usable residues		
Total usable residues such as branches and small logs		472.1

From Table 3.3 , the total replanted area for 1988 is estimated to be 58120 ha. Using data from Table 3.4, the total quantity of usable residues left behind in the field is:

472.1 * 58120 ha/y = 27.438 million t/y [1]

3.4.2 Residues from logs extracted

The logs that are extracted undergo a series of primary and secondary processing from which a substantial quantity of residues are derived. The sources of residues are schematically represented in Figure 3.1 and a sample calculation for the year 1988 is taken as an example.

Based on a 14 % or 100.5 t/ha of logs extracted, the total quantity of logs extracted from the replanting areas is:

58120 * 100.5 = 5.841 million t/y [2]

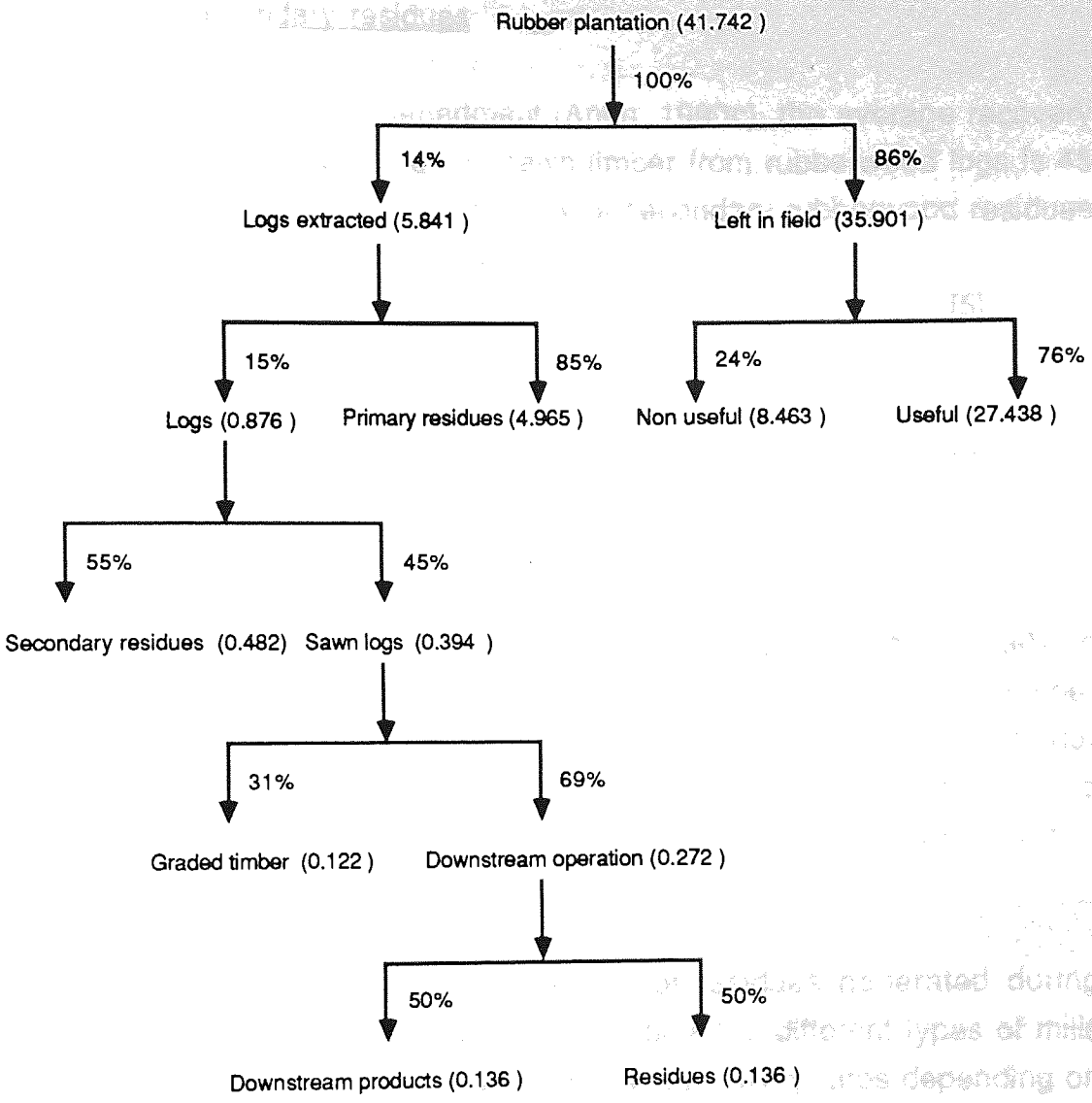


Figure 3.1 Rubberwood Residues Generated (million t/y)

3.4.2.1 Primary processing

Out of the total quantity of logs extracted, only 15 % for the primary processing to timber due to the presence of excessive defects and severe attack by insects during storage time (Khoo et al., 1985). Thus the total residues derived from primary processing is:

5.841 * 0.85 = 4.965 million t/y [3]

The quantity of the good quality logs produced is:

5.841 * 0.15 = 0.876 million t/y [4]

3.4.2.2 Secondary residues

According to the Forestry Department (Anon, 1990c), the average recovery rate for secondary processing into sawn timber from rubberwood logs is 45 %. Thus from equation [4], the quantity of secondary rubberwood residues derived from secondary processing is:

$$0.876 * (1 - 0.45) = 0.482 \text{ million t/y} \quad [5]$$

The quantity of sawn timber produced is:

$$0.876 * 0.45 = 0.394 \text{ million t/y} \quad [6]$$

3.4.2.3 Downstream residues

According to the Malaysian Timber Industry Board of Malaysia, (1990), in 1988, an average of 31 % (or 0.122 million tonne) of the total sawn timber produced was exported as graded rubberwood timber while the remainder of 0.272 million tonne was used locally for further downstream processing such as for the production of knock down furniture and other value added products.

It is very difficult to estimate the quantity of residues generated during downstream operations as the wood is distributed to different types of mills which are known to attain significantly different recovery rates depending on the type of end products produced. A mill producing crates and boxes, for example, will produce a higher recovery rate than that of a moulding plant. Hence, a meaningful figure is difficult to arrive at without reliable statistics. Nevertheless a conservative estimate of the quantity of rubberwood residues from downstream processing is 50 % of the total wood input, mainly in the form of sander dust, sawdust and shavings. Thus the quantity of rubberwood residues from downstream processing is:

$$0.272*0.50 = 0.136 \text{ million t/y} \quad [7]$$

3.4.2.4 Total residues

The total quantity of rubberwood residues available in 1988 can be summarised in Table 3.5.

Table 3.5
Total quantity of rubberwood residues available in t/y,1988

Source	Quantity (t/y)
Usable residues left behind	27.438
Residues from primary processing	4.965
Residues from secondary processing	0.482
Residues from downstream processing	0.136
Total quantity of residues generated	33.021

Using the same method of calculation, the projected quantity of rubberwood residues available in Malaysia from 1988-2000 is illustrated in Table 3.6 and Figure 3.2. The quantity of rubberwood residues is based on the assumption that the primary and secondary recovery rates will remain the same for the next 10 years.

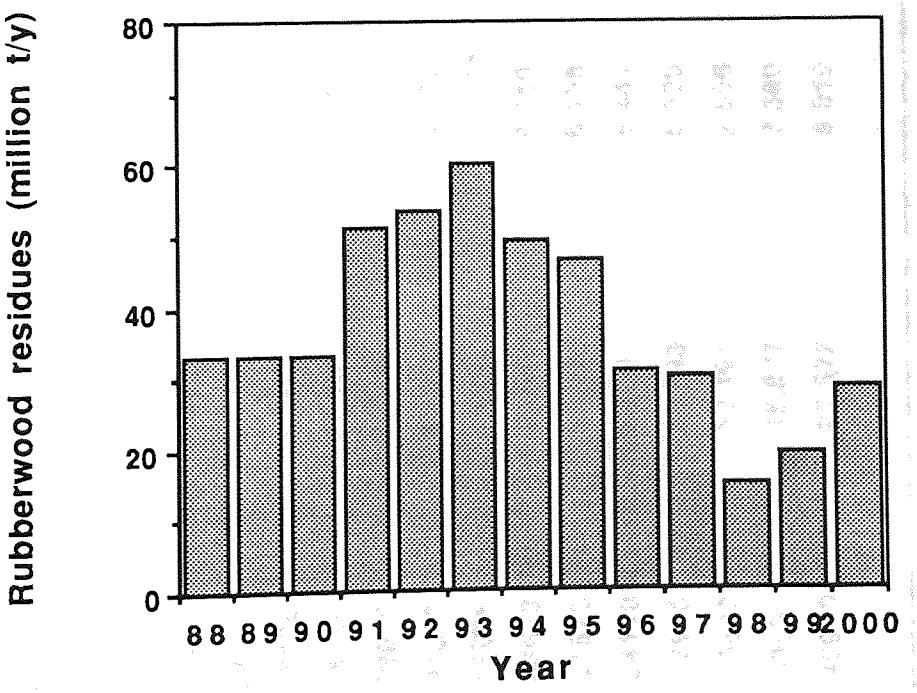


Figure 3.2 **Projected availability of rubberwood residues in million t/y**

Table 3.6
Total projected annual availability of rubberwood in Malaysia (1988-2000)

Year	Total area replanted (ha)	Total useful residues left behind (million tonne)	Total wood extracted (million tonne)	Total primary residues (million tonne)	Total secondary residues (milion tonne)	Total downstream residues (million tonne)	Total annual residues available (million tonne)
1988	58120	27.438	5.841	4.965	0.482	0.136	33.021
1989	58120	27.438	5.841	4.965	0.482	0.136	33.021
1990	58120	27.438	5.841	4.965	0.482	0.136	33.021
1991	89870	42.428	9.032	7.677	0.745	0.210	51.060
1992	94280	44.510	9.475	8.054	0.782	0.221	53.566
1993	105680	49.892	10.621	9.028	0.876	0.247	60.043
1994	86670	40.917	8.710	7.404	0.719	0.203	49.242
1995	81570	38.509	8.198	6.968	0.676	0.191	46.345
1996	54140	25.560	5.441	4.625	0.449	0.127	30.760
1997	52940	24.993	5.320	4.522	0.439	0.124	30.078
1998	25830	12.194	2.596	2.207	0.214	0.060	14.675
1990	33630	15.877	3.380	2.873	0.279	0.079	19.107
2000	49940	23.577	5.019	4.266	0.414	0.117	28.374

The reason for the projected increase in quantity from 1991-1995 is due to the increase in the land area cultivated under rubber 30 years ago. Similarly, the projected decrease in the availability of rubberwood from 1996-2000 is due to the conversion of large areas of rubber plantations into oil palm cultivation in the late 1960's.

Although a substantial quantity of rubberwood is potentially available, the resource is geographically spread over a wide area which makes full utilisation uneconomical and difficult. The widespread distribution of rubberwood is illustrated in Figure 3.3. The quantity of rubberwood residues distributed in different States from 1988-2000 is illustrated in Table 3.7.

From Table 3.7, it can be concluded that in 1988, Johore, Negri Sembilan and Perak generated the largest quantity of rubberwood residues. Collectively, these States accounted for almost 62 % of the total quantity of residues generated. The rest of the States individually produced less than 10 % of the total annual quantity produced.

3.5 PRESENT USE OF RUBBERWOOD RESIDUES

At present none of the usable rubberwood residues left behind in replanting areas are collected and utilised because of the high cost of transporting these low value and bulky material to processing centres. The main sources of rubberwood residues that are being utilised in the country are residues generated from the primary, secondary and downstream processing (Ser, 1990).

Currently, the major utilisation of rubberwood residues in sawmills is in kiln drying operations by combustion to raise steam (Lim and Ratnalingam, 1980). The total quantity of rubberwood used for kiln drying is estimated to be 1.668 million t/y (Hoi and Puad, 1990).

In addition to kiln drying, rubberwood has also traditionally been used as a source of fuel in a number rural industries such as brick making, sheet rubber smoking and tobacco curing. Hoi and Bridgwater (1989) estimated that the amounts of rubberwood consumed by the sheet rubber smoking, tobacco curing and brick making industry are 0.556, 0.056 and 0.056 million t/y respectively.

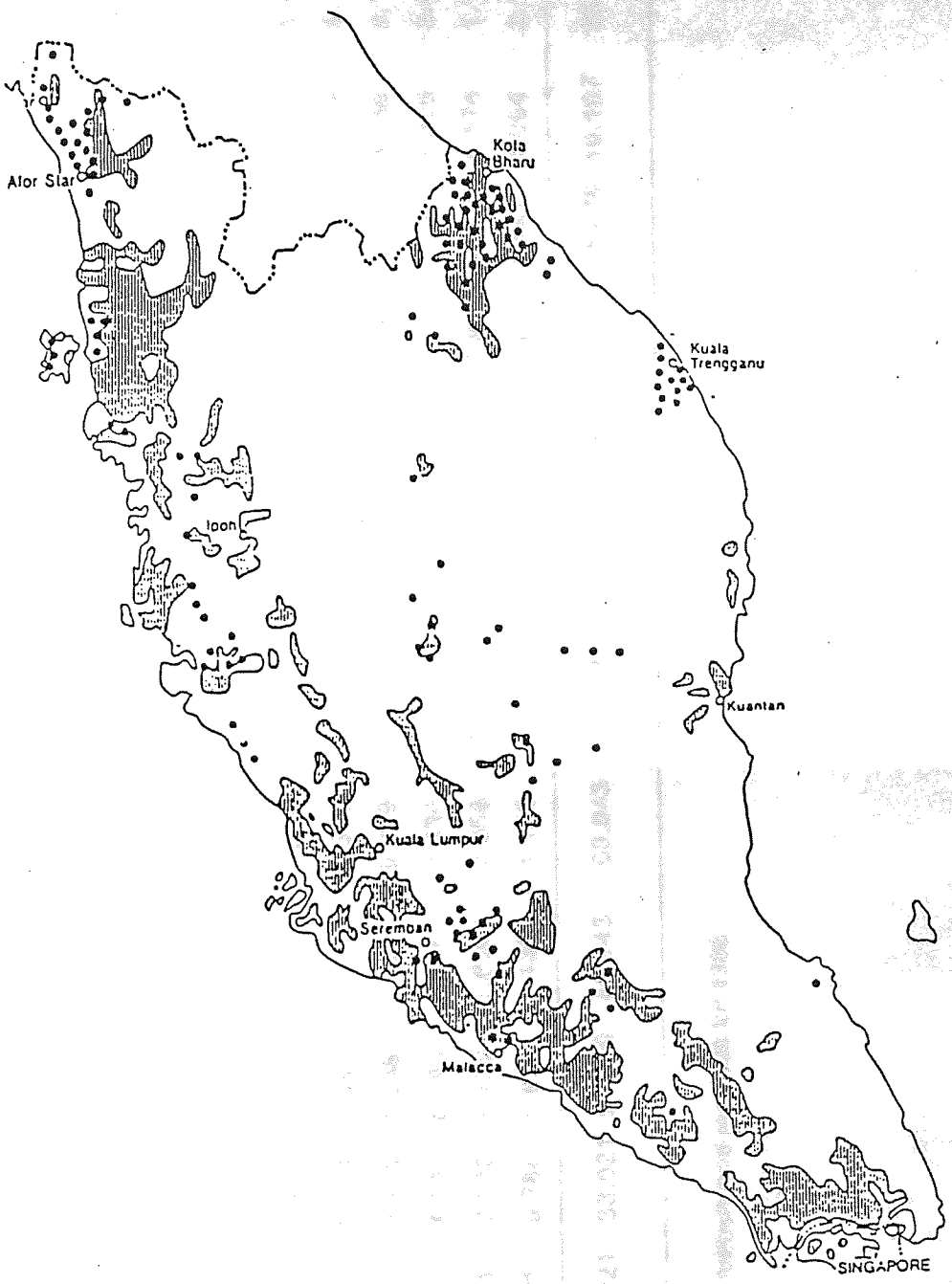


Figure 5.1 Area planted with rubber in Malaysia and main areas where rubberwood is used

Table 3.7
Total annual availability of rubberwood residues by States in million tonne/year

State	1988	1988 (%)*	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Johore	11.685	33.39	11.333	11.342	11.499	22.014	17.431	12.947	13.376	6.527	9.262	3.564	5.628	5.195
Kedah	3.005	9.10	3.330	3.545	5.806	6.521	6.521	8.946	5.828	4.685	3.403	2.140	2.519	3.200
Kelantan	1.191	3.61	1.399	1.601	2.558	3.188	3.188	3.691	2.257	1.297	1.488	0.722	1.060	1.864
Malacca	2.022	6.12	1.665	1.221	2.697	2.298	2.298	0.988	1.742	0.772	0.855	0.545	0.744	0.684
N.Sembilan	4.483	13.58	4.248	4.324	9.495	7.018	7.018	5.324	5.641	4.531	3.340	1.874	2.807	5.616
Pahang	1.895	5.74	2.257	2.274	4.055	6.528	6.528	5.964	4.818	5.885	4.897	2.118	1.606	5.187
Penang	0.705	2.14	0.641	0.725	1.048	0.829	0.829	0.427	0.780	0.589	0.342	0.214	0.259	0.196
Perak	4.385	13.31	4.606	4.631	6.598	7.436	7.436	6.682	6.202	2.944	3.435	1.456	2.256	3.146
Selangor	2.883	8.73	2.821	2.570	6.430	7.658	7.658	3.729	4.637	2.114	1.809	0.600	1.174	1.165
Trengganu	0.757	2.29	0.721	0.788	0.876	1.136	1.136	0.994	1.064	1.416	1.247	1.442	1.054	2.121
Total	33.021	100.00	33.021	33.021	51.060	60.043	60.043	49.242	46.345	30.760	30.078	14.675	19.107	28.374

* Percentage share of total quantity of rubberwood residues for 1988

Beside being used as a source of fuel, a substantial amount of rubberwood is also converted into charcoal where they are used for the reduction of steel in the Malayawata Steel Mill. According to Hoi (1988) , about 1.222 million t/y of rubberwood was used for the production of charcoal in 1988.

Rubberwood residues are also chipped and utilised for further downstream processing such as for the manufacture of particleboard, moulded particleboard, wood cement board and medium density fibreboard. The total quantity of rubberwood residues consumed for the manufacture of these products is estimated to be 0.556 million t/y (Norini et al. 1990). The total demand for rubberwood residues in 1988 is summarised in Table 3.8.

Table 3.8
Estimated quantity of rubberwood residues consumed in Malaysia, 1988

Industries	Quantity (10^6 t/y)
Kiln drying	1.668
Rubber smoking	0.556
Tobacco curing	0.056
Brick making	0.056
Charcoal production	1.222
Other products	0.556
Total	**4.114**

3.5.1 Distribution of rubberwood residues by States

The breakdown of the utilisation of rubberwood residues in the various States is summarised in Table 3.9. From Table 3.9, it can be deduced that the main demand centres for rubberwood residues are Johore (32.9 %) and Perak (17.4 %). In Johore, the wood-based industry is well developed and hence the main use of rubberwood residues is for the kiln-drying of timber. A significant portion of the residues is also used for the manufacture of block board and medium density fiberboard. In Perak, the main demand for rubberwood residues is for charcoal production for the Malayawata Steel Mill in the North and for the kiln drying of timber. Penang (2.2 %) and Trengganu (3.0 %) have the least demand for rubberwood residues.

Penang and Trengganu are not traditional rubber growing states and hence account for the relatively low demand for rubberwood.

Table 3.9
Utilisation of rubberwood residues by states (10^3 t/y), 1988

States	Charcoal	Tobacco	Brick	Rubber	Value-added	Kiln drying	Total	%
Johore	245	3.0	11.1	95	389	612	1354	32.9
Kedah	122	3.0	5.6	72	--	117	320	7.8
Kelantan	60	45.0	2.8	22	--	50	181	4.4
Malacca	36	0.6	1.5	33	--	83	154	3.8
N.Sembilan	146	0.6	2.8	83	56	167	456	11.1
Pahang	86	0.6	3.9	83	56	56	285	6.9
Penang	37	--	--	28	--	28	93	2.2
Perak	367	--	16.7	56	27.5	250	717	17.4
Selangor	86	0.6	5.6	56	27.5	256	431	10.5
Trengganu	37	2.6	6.0	28	--	50	123	3.0
Total	**1222**	**56.0**	**56.0**	**556**	**556**	**1668**	**4114**	**100.0**
(%)		**29.7**	**1.4**	**1.4**	**13.5**	**13.5**	**40.5**	**100.0**

National Tobacco Board Malaysia (1989)
Forestry Department Malaysia (1989)
Statistics Department (1989)
Malaysian Timber Industry Board (1989)

On a national level, rubberwood as a source of fuel for kiln drying, rubbersmoking, tobacco curing and brick making industries collectively accounted for about 56.8 % of the total demand for the residues in 1988. The popularity of rubberwood as fuel was brought about through a long traditional usage of the wood due to its close proximity in areas where the wood based industries are based.

Beside fuel, Table 3.9 also indicates that 29.7 % of the rubberwood residues is used for the manufacture of industrial charcoal for the steel mill. Only 13.5 % of the residues is currently being used for the manufacture of value-added products. However, the percentage share of the value-added sector is expected to increase substantially in the next few years due to the current government's policy of encouraging greater utilisation of rubberwood through value-added products.

As a source of fuel, rubberwood is still the cheapest source of energy for deriving process heat within the sawmill. Table 3.10 illustrates the comparative energy cost of wood to diesel.

Table 3.10
Comparative energy cost for drying in Malaysia, 1988
(Razak and Hoi, 1990)

Energy source	Calorific value MJ/kg	Fuel cost MR$*/MJ	End use efficiency %	Final cost MR$/MJ
Diesel	42.5	0.015	60-80	0.018-0.025
Rubberwood	18.0	0.003	20-30	0.010-0.015

*4MR$ = 1.5 European Currency Units (ECU)

Based on Table 3.10, it can be deduced that for the same amount of energy derived, the comparative cost of energy from rubberwood is between 1.2-2.5 times lower than that of diesel.

3.6 SUPPLY-DEMAND OF RUBBERWOOD RESIDUES

The supply-demand situation of rubberwood residues is illustrated in Table 3.11.

Table 3.11
Supply-demand situation of rubberwood residues by States in 10^6 t/y, 1988

States	Supply[a]	Demand[b]	Availability[c]	%[d]
Johore	11.685	1.354	10.331	35.7
Kedah	3.005	0.320	2.685	9.3
Kelantan	1.191	0.181	1.010	3.5
Malacca	2.022	0.154	1.868	6.5
Negri Sembilan	4.483	0.456	4.027	13.9
Pahang	1.895	0.285	1.610	5.6
Penang	0.705	0.093	0.612	2.1
Perak	4.395	0.717	3.678	12.7
Selangor	2.883	0.431	2.452	8.5
Trengganu	0.757	0.123	0.634	2.2
Total	**33.021**	**4.114**	**28.907**	**100.0**

a Data from Table 3.7
b Data from Table 3.9
c Technical availability = Supply - Demand.
d $\frac{\text{Availability in states}}{\text{Total availability}} * 100$

In terms of residues availability, Johore has the most substantial surplus accounting for 35.7 % of the national share. This is followed by Negri Sembilan (13.9 %) and Perak (12.7 %). These are the three states that offer a significant potential for the utilisation of residues for non-traditional purposes. Given the supply-demand situation, it is also possible to project the annual availability of rubberwood residues up to the year 2000 based on the following scenarios:

a) No change in existing uses

b) An increase of 5 %, 10 % and 15 % in demand of residues for perceived development of the downstream processing industry.

The availability of the residues for each of the four scenarios is summarised in Table 3.12.

Table 3.12
Supply-demand of rubberwood residues under different scenarios in million t/y, 1988-2000

Year	Supply	Demand No change	Surlpus	Demand 5% increase	Surplus	Demand 10% increase	Surplus	Demand 15% increase	Surplus
1988	33.021	4.114	28.907	4.114	28.907	4.114	28.907	4.114	28.907
1989	33.021	4.114	28.907	4.320	28.701	4.525	28.496	4.731	28.290
1990	33.021	4.114	28.907	4.536	28.485	4.978	28.043	5.441	27.580
1991	51.060	4.114	46.946	4.762	46.298	5.476	45.584	6.257	44.803
1992	53.566	4.114	49.452	5.001	48.565	6.023	47.543	7.195	46.371
1993	60.043	4.114	55.929	5.251	54.792	6.626	53.417	8.275	51.768
1994	49.242	4.114	45.128	5.513	43.729	7.288	41.954	9.516	39.726
1995	46.345	4.114	42.231	5.789	40.556	8.017	38.328	10.943	35.402
1996	30.760	4.114	26.646	6.078	24.682	8.819	21.941	12.585	18.175
1997	30.780	4.114	26.666	6.382	24.398	9.701	21.079	14.473	16.307
1998	14.675	4.114	10.561	6.701	7.974	10.671	4.004	16.643	-1.968
1999	19.107	4.114	14.993	7.036	12.071	11.738	7.369	19.140	-0.033
2000	28.374	4.114	24.260	7.388	20.986	12.911	15.463	22.011	6.363

3.6.1 No change in existing uses

Figure 3.4 illustrates a scenario of no change in existing uses. Based on the projected supply-demand situation, there will be an expected annual surplus of between 10.561-55.886 million t/y of rubberwood residues for potential utilisation. The scope for further utilisation of the residues is very substantial.

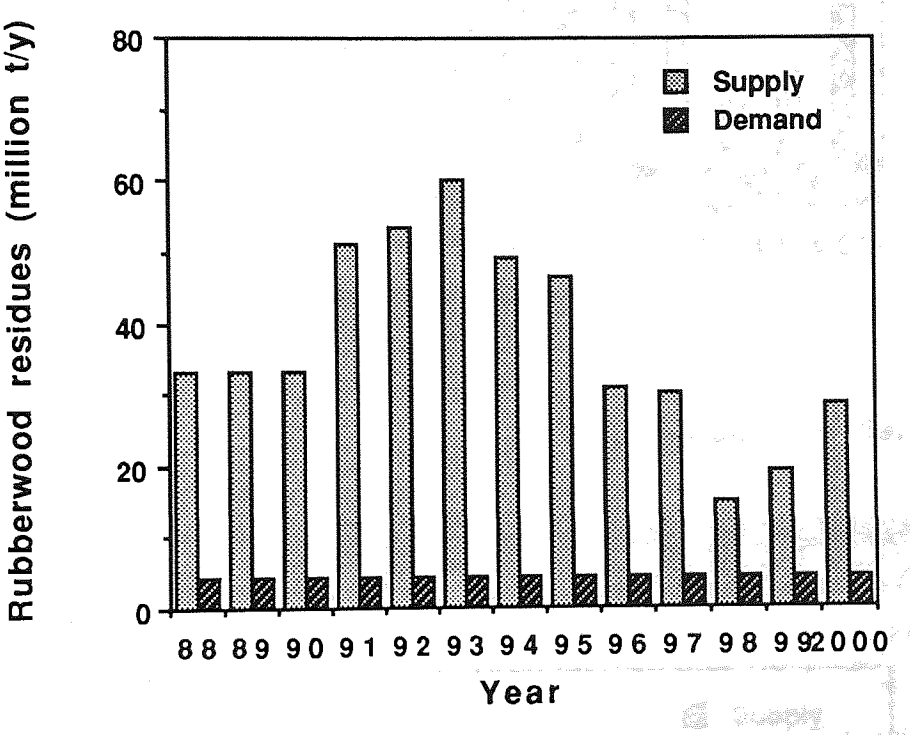


Figure 3.4 Rubberwood residues with no change in demand

3.6.2 An annual 5 %, 10 % and 15 % increment on demand of residues

Figures 3.5, 3.6 and 3.7 illustrate a scenario of a 5 %,10 % and 15 % annual increase in demand of rubberwood residues respectively. For both the 5 % and 10 % scenario, there is no expected deficit of rubberwood residues up to the year 2000. However for the scenario of a 15 % annual increase in the demand of rubberwood residues, the country will be expected to face a potential deficit of 1.968 million tonne in 1998 and 0.033 million tonne in 1999.

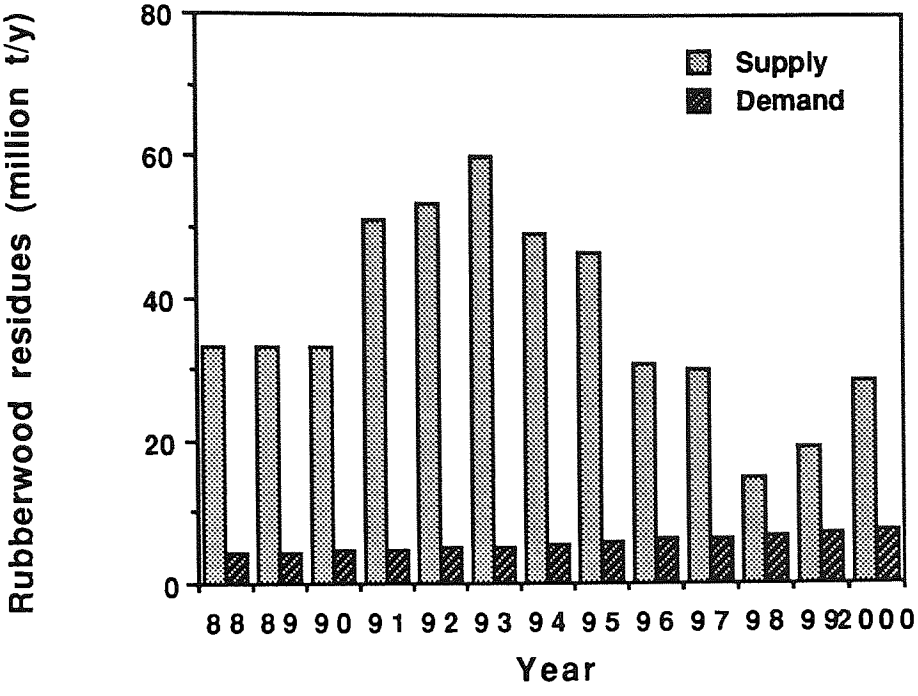


Figure 3.5 Rubberwood residues with 5 % increase in demand

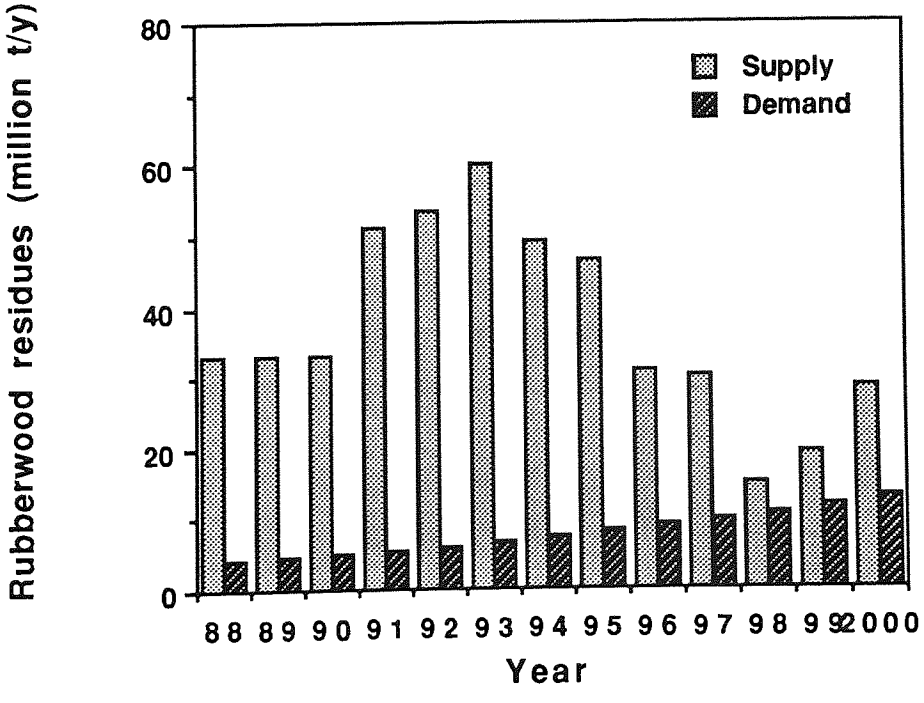


Figure 3.6 Rubberwood residues with 10 % increase in demand

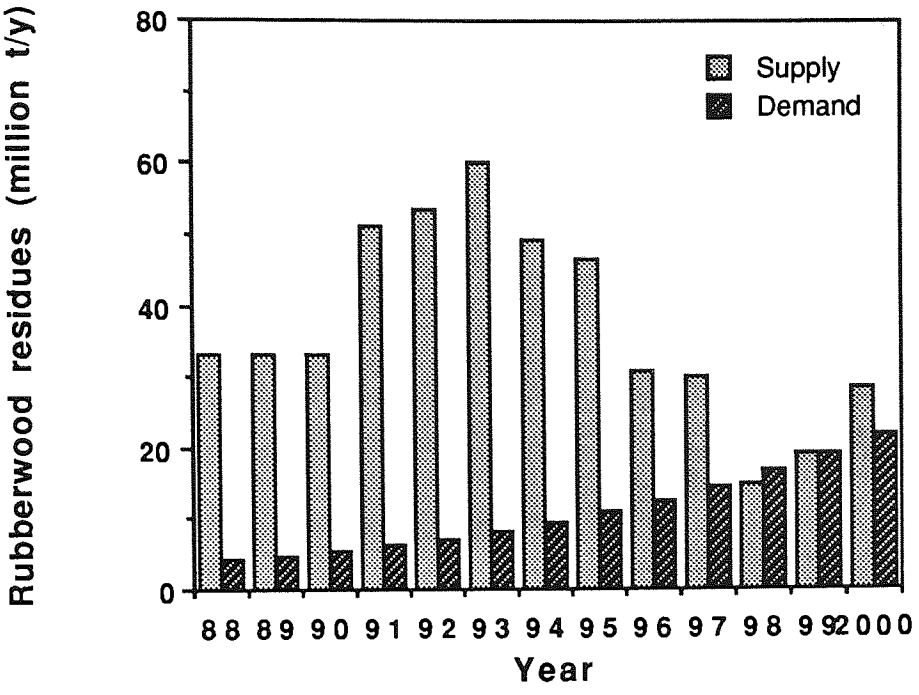


Figure 3.7 Rubberwood residues with 15 % increase in demand

The supply of rubberwood residues over the last 10 years has never been a problem nor posed a major constraint to the past utilisation pattern. Past rubberwood supplies have been relatively well matched with past supply systems. However, based on the above scenarios concerning the various levels of demand, such trends cannot be taken for granted in the future. As rubberwood furniture and other by products are getting more and more internationally accepted and with the escalating difficulty (and hence cost) in extracting rubberwood from remote areas, there will invariably be an intense competition for rubberwood residues from the various end users. This development will inevitably affect the many rural industries using rubberwood residues for energy (see section 3.7).

3.7 RURAL INDUSTRIES USING RUBBERWOOD RESIDUES FOR ENERGY

One of the major features of the demand and utilisation of rubberwood residues as a fuel is that it has traditionally been a rural-based industry. The development of these industries has been accorded high priority as this is one of the main objectives of the New Economic Policy to eradicate rural poverty. However, one of the main components of the Industrial Master Plan

(Anon, 1985a) is the development of further downstream utilisation of rubberwood wastes for value-added products. The combined effect of the two policies will be expected to make the demand for rubberwood residues more competitive in the future especially in areas where rubberwood residues are located within economic radius for utilisation (Hoi, 1990).

For most rural industries like the brick, tobacco and rubber smoking industry, wood is the only realistic fuel both from the economic and technical point of view. This is mainly because most of the nation's commercial energy sources such as natural gas and the national electricity grid are only available in or near urban areas and in many cases are not available at all in rural areas. In view of the constraints in the possibility of changing to commercial fuels, rubberwood will continue to be used as a fuel in rural industries even though it can become equally or more expensive than other commercial fuels in the future.

The possible decrease in the availability of rubberwood residues from 1995 and the expected increase in demand of residues for further downstream processing will ultimately threaten the survival of the traditional industries. In fact Hoi and Puad (1990) have already reported that considerable concern has been expressed in recent years by tobacco curers in Kelantan and by charcoal burners in Perak over the increasing difficulties in getting sufficient rubberwood residues at a reasonable price to be used as fuel.

To ensure the survival of the rural industries and hence the livelihood of a vast majority of the rural population, the government has in recent years embarked on a comprehensive rural energy development programme to look into possible ways to overcome the potential problem of escalating rubberwood fuel cost (KTTP, 1986).

One possibility is to convert rubberwood residues into a secondary source of energy through gasification. With gasification, rubberwood residues can be converted into a gaseous form which can either be burned for process heat or be fed into diesel engines for the production of electricity.

The process heat can then be used in industries where a long steady heat flow is required (such as brick firing, tobacco drying, etc.). The typical conversion efficiency for process heat generation through gasification is

generally reported to be about 85 % if the gas is used hot or 60 % if the gas is cooled (Hoi et al., 1990). In both cases, the resulting efficiency is much higher than the thermal efficiency of 20-30 % on the present conventional combustion reported by Hoi (1988). It is hoped that the higher conversion efficiency will ensure that wood fuel will remain competitive in the future.

A more promising approach is to utilise rubberwood residues both for the generation of process heat and electricity. This approach will in addition offer the possibility of using rubberwood residues to generate electricity to run modern equipment especially in areas where electricity is still not accessible via the national electricity grid. Beenackers and Van Swaaij, (1984) reported that stationary units for electricity generation may be economically feasible although it is very dependant on site specific factors such as feedstock and diesel fuel costs.

3.8 CONCLUSION

Over the next 10 years there will be a substantial amount of rubberwood residues available. Even if the annual demand of residues by the end user rises by 5-10 %, there are still projected substantial surpluses available. The challenge in the fuller utilisation of rubberwood residues is still its economic availability to the many current and potential end users.

In terms of the geographical distribution of rubberwood residues Johore, Negri Sembilan and Perak offer the biggest opportunity for the non traditional users of the rubberwood residues. Besides the use of residues for the generation of energy, the residues can also be used for the production of other value added products such as medium density hardboards, scrimbers and other reconstituted panel products.

In the next 10 years, the greatest use of rubberwood residues will continue to be as fuel for rural industries such as tobacco curing, brick making, rubber drying and for the kiln drying of timber. The biggest problem in utilising more wood for energy is its economic competition from other end users. To remain competitive, the rural industries have to reduce fuel cost. One of the possible ways of reducing rubberwood fuel cost is through the use of better technology. Gasification of rubberwood has been identified as one of the possible technologies.

CHAPTER 4

CHEMISTRY OF GASIFICATION AND LITERATURE REVIEW ON DOWNDRAFT GASIFIERS

4.1 HISTORY OF GASIFICATION

The historical information available on this technology was reviewed by Foley and Barnard, (1983), Anon, (1979), Littlewood, (1977), Overend, (1977) and Kaupp and Goss, (1981). The history of gasification can be dated to as far back as 1669 when Thomas Shirley conducted crude experiments with carburated hydrogen (Goldman and Clarke, 1939; Wyer, 1906). 30 years later Dean Clayton obtained coal gas from pyrolytic experiments. However, the first confirmed use of producer gas (from coal) was reported in 1792 when Murdock generated gas from coal and used it to light a room in his house. For many years after Murdock's development, coal gas was one of the principal fuels used for lighting purposes in England. Although its importance declined due to the development of electricity, producer gas nevertheless remained an important fuel for heating and cooking.

According to the historical review, experiments to gasify wood started in 1798 when Lebon tried to gasify wood and make gas out of it (Skov and Papworth, 1974). In 1801, Lampadius proved the possibility of using waste gases from the charring of wood (Woods, 1938). However, the first commercially used gasifier was credited to Bischof who built a large unit at the iron works of Audincourt, France in 1840. Since then many researchers and engineers have tried to improve on producer gas technology. The more notable breakthroughs were the Siemens gas producers built in 1861 because they were considered the first successful units to use low grade fuel for the generation of combustible gases in furnaces. By the turn of the nineteenth century there were three significant events that saw the beginning of the modern gas producers. The Dowson gas producers built in 1878 can be considered as the starting point of the modern day gas producer system. The introduction of the Mond by-products process proved for the first time that other valuable products such as ammonia could be obtained via gasification. The residual gas from this process was low in heating value but could still be used for industrial heating purposes. The

third was the introduction of the Bernier suction gas producer in 1895 which saw the beginning of the use of the gas producer in small compact units.

The period between 1930-40 can be considered as the development decade for small portable gas producer systems. New concepts such as downdraft and crossdraft gasifiers were either developed or improved further over the earlier models. By 1939, there were more than 10,000 gas producers in Europe alone (Cash and Cash, 1940; Goldman and Clarke, 1939; Rennie, 1930; Telford, 1940; Twelvetrees, 1944).

The beginning of World War II saw the widespread use of producer gas. In Continental Europe, there were as many as 100000 gas producers. During the War, wood and charcoal were the preferred feedstocks for gas producers (Hurley and Fitton, 1959; Kralik, 1943; Lang, 1943; Lindmark, 1944). However, the end of the War saw renewed supplies of liquid fossil fuels which brought about the reconversion of engine systems to run on gasoline and diesel. The shift away from producer gas operations was evidently illustrated in the lack of research done in this field. The number of publications in major engineering indexes dropped sharply from several hundreds per year to less than 10 per year between 1950-70 (Bailey, 1979; Foley and Barnard, 1983; Kaupp and Goss, 1981). The only substantial research done in this field during this period took place in Sweden where considerable improvement of the gas cleaning system and the modifications of diesel engines for producer gas took place (Anon, 1979).

The energy crisis in the 1970's brought about the revival of gasification around the world and much of the present work today concentrates on the revival of the old ideas and technologies during the Second World War. However the renewed interest resulted in the development of small gas producers that can use fuels other than wood and coal (Doner and Baile, 1979; Tookey, 1984).

4.2 TYPES OF GASIFIER

A moving bed gasifier is a very simple device, consisting usually of a cylindrical container filled with fuel, an air inlet , a gas outlet and a grate. It can be manufactured out of fire bricks, steel, concrete or even oil barrels (Rambush, 1923; Cruz, 1980; Groeneveld and Van Swaaij, 1980). If

properly designed and operated, the plant is highly reliable and does not require maintenance other than the periodic removal.

Many different kinds of reactor have been developed for the gasification of carbon containing fuels. Some of the different types available today are the moving bed (Beenackers and Van Swaaij, 1984), fluidised bed (Maniatis, 1986), entrained flow (Beenackers and Van Swaaij, 1984), rotary kiln (Miller, 1983) and molten salt gasifier (Maund and Earp, 1988; Moffat and Kohl, 1984). There are a variety of criteria for the classification of the different kinds of reactor. Reed, (1981) classified gasifiers according to different process variables such as method of gas-fuel contact, ash form and gas pressure.

An alternative way of classifying gasifiers is by 'density factor', which is defined as ratio of the volume of biomass present in the reactor during normal operating conditions to the total reactor volume (Maniatis, 1986). The density factor allows gasifiers to be classified into two categories and these are as follows:

1) Dense phase reactor with a density factor in the range of 0.3-0.6.
2) Lean phase reactor with a density factor in the range of 0.05-0.2 (Bridgwater and Double, 1988).

4.2.1 Dense phase gasifiers

There are a variety of dense phase gasifiers of which the three main types reported in the literature are: updraft gasifier, downdraft gasifier and cross-draft gasifier. The similarities between these gasifiers are the existence of distinct drying, pyrolysis, oxidation and reduction zones within the reactor (see section 4.5) and the downward flow of the fuel by gravity (Overend, 1977; Hos and Groeneveld, 1983; Kumar et al., 1984). However, the main difference between the gasifiers is the relative motion of the gas phase to the solid phase within the reactor.

In updraft gasifiers, gas and solid fuel flow in an opposite direction. The gas flows upwards through the reactor and the pyrolysis gases do not pass through a high temperature oxidation zone resulting in a product gas with a high tar content (Brock, 1974; Shand and Bridgwater, 1984; Payne et al. 1985; 1985a; 1986).

In downdraft gasifiers, both the fuel and the gas flow downward through he reactor enabling the pyrolysis gases to pass through a hot bed of char which is supported by the grate. This results in the cracking of most of the tars into non-condensible gases and water. Downdraft gasifiers are usually equipped with a restriction either in the form of a throat or choke plate (Cruz, 1980; Graham and Huffmann, 1981; Rickey et al., 1985; Shaw, 1985; Silva et al., 1985; Sonnenberg et al., 1985; Tatabaie, 1982; Trezek and Glaub, 1987; Walawender et al., 1985; Williams and Horsfield, 1987). This restriction is located at or below the oxidant inlet in order to improve tar cracking and the production of a fairly clean tar-free gas. Downdraft throated gasifiers will be discussed in more detail in section 4.5.

In crossdraft gasifiers the gas flows at right angle to the fuel bed across the gasifier. This is achieved by the introduction of air on one side of the gasification chamber, normally through an inlet nozzle that brings the air to the centre of the combustion zone. The gas outlet is on the opposite side. Although the product gas contains a high level of tars, when wood is used as feed, this type of gasifier gives a shorter response time to load changes and hence is more suitable for engine use. Crossdraft gasifiers are more suitable for operation with char because of lower tar content compared to wood (Clift and Ortner, 1984; Hatter, 1937; Ruedy, 1944; Sirois and Calhoun, 1985).

Of the three types of dense phase gasifier, updraft gasifiers are the oldest type of gasifier in use and have been used mainly for coal gasification (Reed et al., 1988; Kaupp and Goss, 1981; Anders, 1990). However, this type of gasifier produces a gas that contains large amounts of tar that are undesirable for engine use (Larson and Rundstrom, 1988; Mahin, 1984). The downdraft gasifier was then developed to reduce this tar problem by forcing unreacted tars through a high temperature and oxygen zone in order to crack the tar.

The comparative advantages and the operational principles have been reviewed by Maniatis, (1986); Groenevald, (1980); Beenackers and Van Swaaij, (1984); Buekens and Schoeters, (1985); Lepori et al., (1983). The relative advantages and disadvantages of dense phase gasifiers are summarised in Tables 4.1 and 4.2.

Table 4.1

Dense phase gasifiers: Advantages and Disadvantages

Advantages	Disadvantages
Updraft	
Low gas exit temperature	High tar yield
High char conversion	Low specific gasification capacity
Low ash carry over	Feed required to be uniformly sized and no fines
Simple construction	Bridging or channeling of feed
Easy to scale-up	Ash fusion on grate
Suitable for wet fuel	Difficult to feed
(Moisture greater than 25 %)	Poor turndown
Downdraft	
Low tar yield	High gas exit temperature
High char conversion	Low specific gasification capacity
Low ash carry over	Certain turndown ability
Simple construction	Feed required to be uniformly sized and no fines
Quick response to load change	Difficult to scale-up
	Ash fusion on grate possible
Crossdraft	
Low reactor weight	High tar in product gas
Low ash carry over	Low specific capacity
Quick response to load change	Poor turndown
Better gas flow	Difficult to scale up

Table 4.2

Operating principles of dense phase gasifiers

(Hos and Groeneveld, 1987)

	Updraft	Downdraft	Crossdraft
Feed flow	gravity	gravity	gravity
Oxidant flow	upwards	downwards	horizontal to feed
Oxidant injection	at grate	at top(open core) at throat(throated)	lateral
Product gas outlet	Top of reactor	bottom, under grate	side of reactor
Carbon conversion	100 %	< 100 %	< 100 %
Maximum temperature	1000-1200°C above grate	1000-1200°C at throat (throated) reaction zone (open-core)	1400°C oxidation (charcoal)

4.2.2 Lean phase gasifier

This type of gasifier is homogeneous with no distinct reaction zones within the reactor The main types of lean phase gasifier are the fluidised bed gasifier, circulating fluid bed gasifier and entrained flow gasifier. All these gasifiers were first designed for the gasification of coal (Groeneveld and Westerterp, 1979). As the thesis is confined to a throated downdraft gasifier, lean phase gasifiers are not reviewed.

4.3 MAJOR PROPERTIES OF WOOD RELEVANT TO GASIFICATION

There is substantial information available on properties of wood for thermochemical conversion. Wood fuel is available in various physical forms and each one needs a specially designed gasifier for a limited range of biomass specification. Hence, the characterisation of wood properties is important for process design. The most significant properties of wood that are known to influence the gasification process are the moisture content, absolute and bulk density, wood size, chemical composition of wood (such as the proximate and ultimate analysis) and the higher heating value (Fengal and Wegner, 1984; Mitchell and Pearce, 1984; Grabowski and Bain, 1981; Milne, 1981; Goldstein, 1981; Ebeling and Jenkins, 1984; Shafizadeh and Degroot, 1976).

4.3.1 Moisture content

The moisture content of wood is generally determined by the type of wood, its origin and treatment before use. Moisture in wood can be fundamentally subdivided into three categories namely:

1) Inherent moisture that wood holds when it is in equilibrium with ambient atmosphere. Inherent moisture is held in the capillary openings in wood.
2) Surface moisture is the moisture which occurs on the surface and is in excess of inherent moisture.
3) Decomposition moisture is the moisture formed from organic compounds of the wood as they are decomposed by heating. Generally this occurs in a temperature range of 200-250°C (FAO, 1986; Reed, 1985; 1985a; Reed and Markson, 1985).

The moisture content cited in literature usually refers to the inherent plus surface moisture. In the timber trade it is common to defined it on a wet basis as:

$$\text{Moisture content} = \frac{\text{wet weight-dry weight}}{\text{wet weight}} * 100\ \%$$

In Malaysia the average moisture of freshly felled rubberwood is seldom below 20 % wet basis due to the high humidity of the country. For gasification it is always desirable to use wood of low moisture content as heat is required to evaporate the moisture from the feed and this energy is provided from the partial combustion of wood. Therefore high moisture contents reduce the thermal efficiency of the gasifier and also result in low gas heating values of less than 2.5 MJ/Nm^3 (Bridgwater and Double, 1988; Reed and Markson, 1983; Reed et al., 1985; Rossi, 1984). In downdraft gasifiers, high moisture content not only gives rise to low gas heating values but also to low temperatures in the oxidation zone and this can lead to insufficient tar converting capability if the gas is used for engine applications (Bhagwat, 1986; Kaupp, 1984; Parikh and Arikkat, 1985; Parikh et al., 1988). The Swedish Experience (Anon, 1979) reported that a moisture content of less than 35 % (wet basis) is required to generate reasonably good quality gas suitable for engine applications. However, Ekman and Asplund, (1973) and Feldman et al., (1979) reported that moisture contents of as high as 50 % have been successfully gasified in downdraft gasifiers.

4.3.2 Absolute and bulk density

The absolute and bulk density of wood is important for process design in terms of storage and handling (Bacon et al., 1982; Bridgwater et al., 1986; Chern et al., 1987). It is also a very good indicator of how densely the wood will pack into the reactor. Wood with high bulk densities will require less reactor space for a given refueling time. On the other hand, low bulk fuels sometimes give rise to insufficient flow under gravity resulting in low gas heating value and possibly burning char in the reduction zone (Brandini, 1983; Cruz, 1984; Coovattanachai, 1985).

4.3.3 Wood size

Downdraft gasifiers are limited in the range of wood size as feed to the reactor (see section 4.61). Under sized and non uniform wood will cause

fuel flow problems in the gasifier as well as larger pressure drop across the gasifier. Excessively large wood size will give rise to reduced reactivity of the fuel resulting in start up problems and poor gas quality. It is also believed that it is the cause of slag formation because the fuel will stop flowing at an unchanged air input rate. The air fuel ratio will then increase locally and and reach a temperature high enough to induce slag formation (Zerbin, 1984; Winship, 1980; Walawender et al., 1988; Tatabaie, 1987).

4.3.4 Chemical composition of wood

The properties of wood that are important to gasification are the ultimate and proximate analysis (see chapter 6). The ultimate analysis of wood is the elemental analysis of wood namely carbon, hydrogen, oxygen, nitrogen and sulphur. The ultimate analysis provides information on the heating value of wood (Beaumont and Schwob, 1984; Wenzl 1970). The ultimate analysis of wood does not indicate the suitability of wood for gasification. However, it is the main tool for predicting the gas composition and temperature limits of the gasifier through mass and energy balances (Chee et al., 1988; Ebeling and Jenkins, 1985).

The proximate analysis of wood is the combustible volatile matter, fixed carbon, and ash content. Wood generally contain between 70-90 % of volatile matter which makes it more reactive during gasification when compared with coal (Grabowski and Bain, 1981; Kjellstrom, 1985). However, high volatiles in wood will generally give rise to high tar content in the gas. A substantial quantity of this tar will have to be removed before it can be used in internal combustion engines (see section 4.8) (Dasappa et al., 1985; Dennetiere, 1980; Doner and Baile, 1979).

Wood generally contains very low ash, typically less than 3 % on a dry basis (Mendis et al., 1987; Reed and Levi, 1984; Walawender et al., 1987). The amount of ash in wood will affect the gasification process in 2 ways, namely:

1) For high ash wood fuels (such as those found in most tropical hard wood), the ash must be removed quite frequently or continuously from the gas producer thus incurring additional ash removal systems and hence possible additional ash removal cost (Grover, 1989; Kaupp and Goss, 1981; Kjellstrom, 1985).

2) For high ash wood fuel, there is a higher tendency for ash fusion at the grate which in turn affects the gasification process (Graboski and Bain, 1981; Kaupp and Goss, 1981; Kjellstrom, 1985).

4.3.5 Heating value of wood

In most literature, the heating value of wood is expressed either as the higher heating value or lower heating value. The higher heating value is the heat evolved in the combustion of wood into carbon dioxide and liquid water, whereas the lower heating value is the heat evolved when the products of combustion are gaseous carbon dioxide and water vapour. In a combustion processes, the latent heat of the produced water vapour is not usable and hence the lower heating value is a measure of the usable heat of combustion. However, in thermodynamic calculations, the heat of reaction is given for the reactants and products in the standard state and the higher heating value is thus the thermodynamically correct method of measuring the heat of combustion.

As gasification is primarily an energy process, the heating value of wood is the dominant energy input to the process in energy balance terms. Hence, the higher heating value has a significant influence on the energy balance and hence the performance of the gasifier (Chee et al, 1988a; Graboski and Bain, 1981).

4.3.6 Wood as fuel for gasification

The important characteristics of wood as fuel for gasification are the relatively high volatile content, and ease of processing to a uniform shape and size. Kjellstrom (1980) listed the ideal wood specifications for downdraft gasifiers to be the following:

1) Length to diameter ratio should be less than 2 and with a low percentage of fines.
2) Bulk density should not be less than 200 kg/m^3.
3) Moisture content should be less than 30 %
4) Ash content should be less than 6 % with an ash fusion point of above 1150°C in a reducing atmosphere.

The properties of wood suitable for gasification are summarised in Table 4.3.

Table 4.3

Chemical composition of wood (Kjellstrom, 1981)

Elements	Ultimate analysis (dry basis)
C	50-54 %
H	4-7 %
O	40-44 %
N	0.1-0.5 %
Proximate analysis (dry basis)	
Volatile matter	77-87 %
Fixed carbon	13-21 %
Ash content	< 6 %
Moisture content	<30 %wet basis
Bulk density	>200 kg/m^3

4.4 CHEMISTRY OF GASIFICATION

Gasification is the conversion of a carbon containing solid such as wood, with a limited amount of oxidising agent (such as air, oxygen or steam or various mixtures of these three reagents) at an elevated temperature to produce a gaseous product consisting mainly of hydrogen, carbon monoxide, carbon dioxide, methane, water, nitrogen (if the gasifying agent is air) and possibly higher hydrocarbons such as ethane, ethene and propane. However, in reality, in addition to the gaseous products, a solid residue of char (containing mainly carbon and ash), tars and condensate (containing mainly water) are also produced. For many applications, such as the use of the product gas for engine operations, the non gaseous products, particularly tars, are undesirable and must either be removed and/or their production minimised (see section 4.8 on dual fuel performance on engine).

Gasification is not a simple process. The physical and chemical processes in the gasifier are not completely understood and the gap between observed data obtained from practical operations and data obtained under controlled laboratory conditions is still being investigated around the world (Breag, 1979; Cogliali, 1986; Corella et al., 1984; Feldman et al., 1979; Feldman et al., 1985; Gumz, 1950; Kaupp, 1983).

During the process of gasification, wood undergoes a complex physical and chemical change starting with the drying or removal of water contained as

moisture. The dried wood is then pyrolysed or thermally decomposed. Finally, the pyrolysis products, condensible vapours and char undergo gasification where they are concurrently oxidised or reduced to permanent gases. Distinct zones can be identified for these four processes. In this review, the gasification process is described for a conventional throated downdraft gasifier where the four process can be conceptually considered as taking place in a series of zones as illustrated in Figure 4.1.

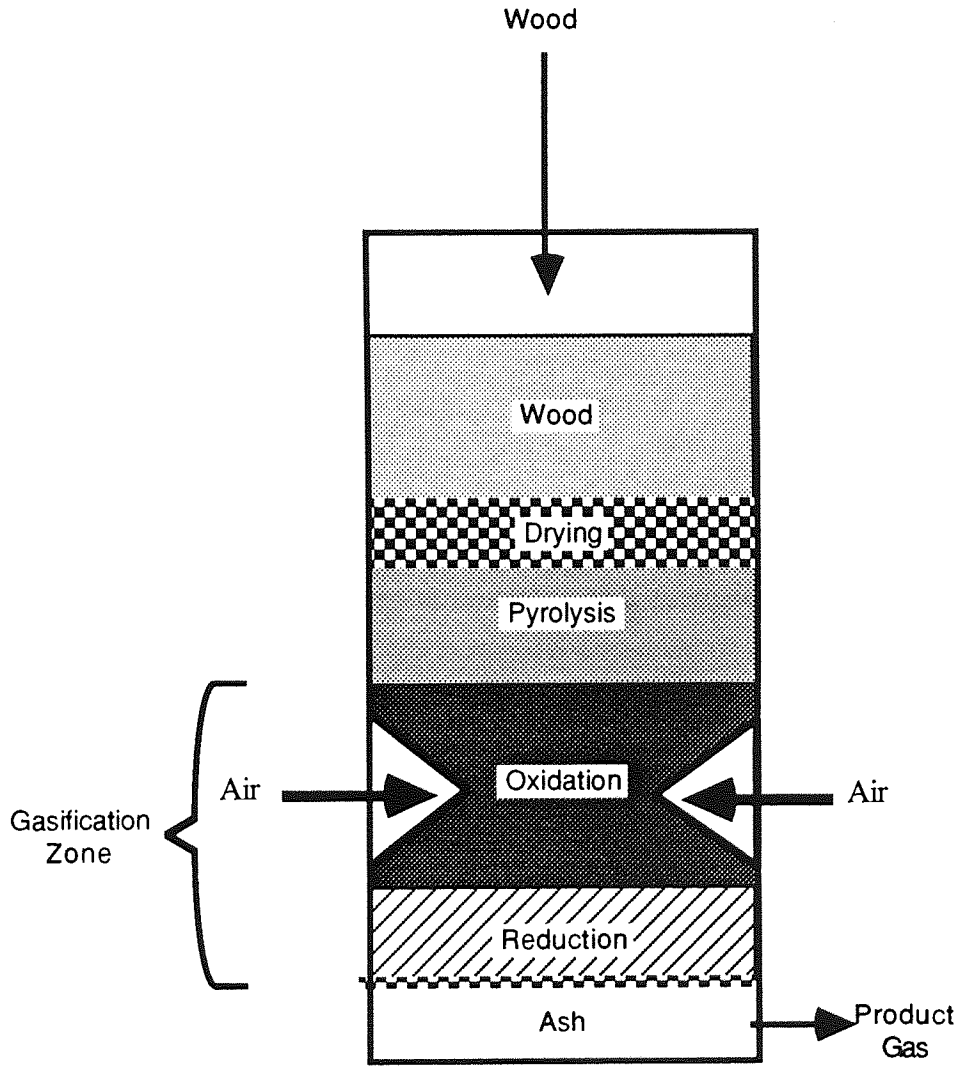


Figure 4.1 Reaction zones in a throated downdraft gasifier

4.4.1 Drying process in a downdraft gasifier

This is the process whereby moisture contained in wood is removed by evaporation. It is believed that the heat required for this process is provided by the heat transfer from the hotter lower zones of the reactor by recirculation

of hot gas produced from the reaction zone (Kaupp and Goss, 1981; Kaupp, 1983a; Groeneveld et al., 1980).

4.4.2 Pyrolysis process in a downdraft gasifier

The dry wood from the drying zone is then pyrolysed or thermally degraded at temperature above 250°C (Groeneveld, 1980; Reed et al., 1988). The pyrolysis products can be grouped into three main categories of solid, liquid and gas.

4.4.2.1 Char

This is the solid residue of the wood consisting mainly of carbon together with some hydrogen, oxygen, ash and some volatiles from incomplete pyrolysis. The analysis of char is given in chapter 6 (Harris, 1989).

4.4.2.2 Condensates

These are liquid pyrolysis products consisting of a complex mixture of more than 200 different compounds (Brown et al., 1987; Knoef et al., 1987; Soltes and Elder, 1981). The condensate contains two phases, an organic and an aqueous phase. The organic phase consists mainly of insoluble matter and hydrocarbons while the aqueous phase contains up to 99 % of water (Harris, 1989). All these products are vapours at the pyrolysis temperatures of 250-450°C (Hos and Groeneveld, 1983; Macrae, 1966; Kaupp and Goss, 1981).

4.4.2.3 Gases

This is a mixture of non-condensible gases such as CO, CO_2, H_2 and light hydrocarbon such as CH_4, C_2H_4, C_2H_6, C_3H_8 and C_3H_6. The relative proportion of them depends on the pyrolysis reaction conditions namely temperature, heating rate, wood moisture content, particle size, composition of the ambient atmosphere, pressure and vapour residence time (Evans and Milne, 1987; Reed et al., 1988).

4.4.3 Gasification stage

In this stage the pyrolysis products undergo a series of oxidation and reduction processes to produce a final product gas which is mainly CO, CO_2, H_2, CH_4 and H_2O. Gasification generally take place at temperatures above 700°C (Reed and Jantsen, 1979; Rossi, 1984; Skov and Papworth 1975).

Much of the work in the literature does not cover the reactions of the tars in the gasification stage because the process is very complex and not well established. They may be gasified via thermal cracking or reaction with the gasifying agent and other pyrolysis products at temperatures above 250°C. Typical reaction mechanisms can be depicted as follows (Reed et al.,1985):

$$\text{Wood, } C_6H_{10}O_5 \rightarrow C_6H_9O_3 \text{ (tars)}$$

$$C_6H_9O_3 \rightarrow CO + H_2O + CO_2 + \text{hydrocarbons}$$

$$C_6H_9O_3 + O_2 \rightarrow CO + H_2O + CO_2$$

The reactions of solid and gaseous pyrolysis products with each other and/or with the gasifying agent have been thoroughly discussed by Reed and Markson, (1983a), Reed et al., (1984) and Groeneveld and Van Swaaij, (1980). These reactions can be grouped into heterogeneous reactions including all the solid-gas reactions and the homogeneous or gas phase reactions. These reactions are summarised in Table 4.4.

Table 4.4
Gasification reactions

1) Heterogeneous reactions			
	Oxidation of carbon		
4.1	$C + 1/2O_2$	$\rightarrow CO$	$\Delta H = -110.6$ kJ/kmol
4.2	$C + O_2$	$\rightarrow CO_2$	$\Delta H = -393.8$ kJ/kmol
	Bourdouard reaction		
4.3	$C + CO_2$	$\rightarrow 2CO$	$\Delta H = 172.6$ kJ/kmol
	Water gas reaction		
4.4	$C + H_2O$	$\leftrightarrow CO + H_2$	$\Delta H = 131.4$ kJ/kmol
	Methane formation		
4.5	$C + 2H_2$	$\rightarrow CH_4$	$\Delta H = -74.93$ kJ/kmol

Table 4.4 continued

2) Homogeneous reactions

	Water shift reaction		
4.6	$CO + H_2O$	<=> $CO_2 + H_2$	ΔH = 41.2 kJ/kmol
	Oxidation		
4.7	$CO + 1/2O_2$	--> CO_2	ΔH = -283.8 kJ/kmol
	Reduction		
4.8	$2CO + 2H_2$	<=> $CH_4 + CO_2$	ΔH = -247.3 kJ/kmol
	Oxidation		
4.9	$H_2 + 1/2O_2$	--> H_2O	ΔH = -241.8 kJ/kmol
	Reduction		
4.10	$CO_2 + 4H_2$	<=> $CH_4 + 2H_2O$	ΔH = 164.7 kJ/kmol
	Reduction		
4.11	$CH_4 + H_2O$	<=> $CO + 3H_2$	ΔH = 201.9 kJ/kmol

4.5 THROATED DOWNDRAFT GASIFIERS

There are generally two main varieties of downdraft gasifier, namely the conventional throated gasifier (Reed et al., 1983; Kaupp and Goss, 1981) and the more recently developed open core gasifier (Earp, 1988; Reines, 1988). By 1986, Bridgwater et al., (1986) reported that there are at least 20 companies manufacturing downdraft gasifiers systems. At least 70 units are installed in developing countries (Mendis et al., 1987; World Bank 1986).

The throated gasifier has a constriction or a throat located near the base of the reactor where the oxidant or gasifying agent is introduced (Figure 4.1). The throat can be in a form of a cone (Baker et al., 1985; Bangham and Benett, 1940; Cruz, 1978) or a simple horizontal choke plate (Anon, 1940; Anon, 1941; Baker, 1965; Ward and Morrison, 1942; L'Ecuyer and Huffmann, 1981).

In both types of throat , the gasifying agent is introduced either through a central air injection nozzle or through wall mounted tuyeres located just above the throat. The gasifier is normally circular in cross-section, although gasifiers with rectangular cross-section have also been reported (Birchfield and Shepherd, 1984; Kutz et al., 1983).

Throated downdraft gasifiers are normally operated with air as the gasifying agent. Pure oxygen and mixtures of oxygen/air and oxygen/steam have also been used at laboratory scale (Makray et al., 1987; Doner and Baile, 1979).

The combination of air injection and throat results in the production of a very low tar gas suitable for internal combustion engines. Throated gasifiers has thus been mainly used for fueling internal combustion engines to generate electricity or to power vehicles (Goss, 1980; Kjellstrom, 1989; Garcia et al., 1991).

4.5.1 Tar cracking mechanism

The interest in the throated downdraft gasifier has been mainly been its ability to crack tar. Tar is converted or cracked in the reactor either by thermal degradation at high temperature, or by partial oxidation with oxygen (see section 4.4.3). In order to minimise the tar content in the product gas, the primary tar laden gas is passed through a zone of high temperature and high oxygen concentration to partially oxidise or thermally crack the tars.

The introduction of a gasifying agent into the reactor provides the necessary oxygen for partial oxidation of all pyrolysis products, including tar. The various components of the pyrolysis products react with the oxygen in the gasifying agent at different reaction rates and are with the order (Field et al., 1967):

$$H_2 > CH_4 > CO > C$$

The reactions are exothermic and raise the temperature within the reactor to more than 850°C. This will enable the tars to be thermally degraded. Further tar cracking may also take place in the char in the reduction zone if the temperature is above 850°C.

The rate of reaction of oxygen with the pyrolysis products is very rapid. Because of this, the air jets will have limited penetration in the bed resulting in uneven temperature distribution across the reactor bed, where the hottest zone will be nearest to the injector.

Groeneveld (1980), reported that in an experiment involving the combustion of charcoal, all the particles are consumed within a two particle diameter, which implies that a maximum throat diameter of four particle diameters will

be necessary to ensure that there is no oxygen free zone in the reactor. However, in practice, this is not possible and the occurrence of a oxygen free zone will result in the formation of 'cold-spots' within the reactor which will allow tar to pass through uncracked.

The introduction of a throat will reduce the bed penetration problems by reducing the cross-sectional area of the reactor and hence reduce the required penetration distance of the air jets. The throat also increases the gas turbulence in order to ensure a more uniform side and back mixing (Groeneveld, 1980). Ideally, there should be a hot zone across the reactor so that all tar laden gas can pass through to ensure complete cracking of tar.

Another method to ensure a more uniform distribution of oxidant is the use of more air injectors across the reactor. However, this could result in disturbances in the flow of solids through the reactor, causing bridging or formation of voids which would allow the product gas to escape uncracked.

The important criteria in the design of a throated downdraft gasifier are reported to be the positioning of the air injector relative to the throat, the diameter of the nozzles and the diameter of throat (Cogliali, 1986; Anon, 1979). Kjellstrom, (1989) and Groeneveld, (1980) reported that increasing the distance between the throat and the reactor wall can drastically increase the tar content of the product gas due to the limitation of the air jet penetration.

Groeneveld, (1980) and Hedden et al., (1986) stated that the angle of injection is also important in order to ensure sufficient tar cracking. The most efficient tar cracking occurs when air is injected horizontally into the reactor. This is due to the recirculation of gas within the reactor which will carry tar laden gas back into the hot zones in the vicinity of the reactor and hence increase tar cracking of the product gas. Groeneveld, (1980) also reported that this recirculation effect is important in the design of the gasifier, obtaining a tar free gas when the temperature at the throat wall is as low as 527°C. This, he claims is due to the recirculation of gas within the reactor.

Another method of improving tar cracking mechanism is to minimise the heat loss from the reactor wall in order to ensure a high temperature at the wall. This insulation can be achieved either with the use of high temperature refractory cement and/or by passing the product gas in an annulus

surrounding the reactor. The hot product gas can then be used to preheat the gasifying air prior to injection into the reactor. This will result in increased temperature in the oxidation zone due to increased sensible heat of the oxidant.

Susanto, (1982) however conducted an experiment to recirculate pyrolysis products with the air used for gasification to reduce the tar content. Air was introduced through a pipe on the top of the gasifier. This air also acted as a motive gas in the injector for suction of the recycled gas. The combustor was installed in the discharge of the injector and is mounted on the ash grate which can be rotated. Recycle ratios (which is the ratio of recycled gas rate to air flow rate) in the range of 0.4 to 1.6 resulted in stable combustion of the recycled gas. Table 4.5 shows the effect of recycle ratio on gasification performance. A significant reduction in tar was achieved by recycling pyrolysis gas to the air feed and further reduction in tar was achieved by using a separate combustor. The optimum recycle ratio was about 0.9 or less where the tar was reduced from 1.4 g/Nm^3 (without recycling) to 0.05 g/Nm^3 (with recycling). A similar principal was also used in the Delacott system in the United States (Goss and Lamorey, 1982).

Table 4.5
Effects of recycle and separate combustion of pyrolysis gas on gasification performance

Experiment	Conventional No combustor Throat =20 cm	Recycled Combustion pyrolysis gas	
Recycle ratio*	1.40	1.90	0.85
Air flow, Nm^3/h	31.3	28.02	8.0
Gas composition,dry basis			
H_2	9.6	12.9	15.5
N_2	60.0	56.2	52.6
CO	12.4	13.4	21.2
CH_4	2.5	2.0	0.4
CO_2	17.3	15.5	10.3
Heating value of product gas, kJ/Nm^3	3820.0	3840.0	4480.0
Condensibles in gas	227.4	128.0	57.0
Tar in gas (g/Nm^3)	0.350	0.097	0.048
Temperature at throat ,°C	900.0	-	-

* Recycle ratio = Nm^3 recycle gas/Nm^3 air

4.6 LIMITATION OF THROATED DOWNDRAFT GASIFIER

4.6.1 Fuel limitation

The only purpose of the throat is to encourage tar cracking but it is a physical hindrance to the free flow of fuel. Hence, fuels for downdraft gasifiers must be reduced in size in order to facilitate fuel flow. Throated downdraft gasifiers are therefore not suitable for fuels that exhibit poor flow characteristics such as low bulk density and high ash fuel. Due to the high temperatures in the vicinity of the air injectors, fuels with low ash melting points and/or that have a tendency to form slag at low temperature will also be unsuitable as slag formed in the oxidation reduction zone will flow downwards and then cool and solidify in the cooler parts of the reactor thus obstructing fuel flow (Kaupp, 1984; Reed et al., 1986).

There are also limitations on the particle size. Fuels such as sawdust and rice husk decrease the penetration depth of the air injector in the reactor bed which will lead to formation of cold spots and hence high tar content in the product gas (see section 4.5.2). Large particle sizes are limited by the size of the reactor and the ability of the fuel to be devolatised before entering into the reduction zone.

Particle size distribution can also be considered as a limitation as feed containing different particle sizes and shapes can promote bridging in the reactor (Groeneveld, 1980; Reed and Markson, 1986). Bridging may even hinder the flow of fuel through the bed or form channels which could allow tar laden gas to pass through uncracked.

High moisture fuels are also unsuitable because more heat will be required to remove moisture from the feed. As discussed in section 4.4.1.1, this heat is generated from the oxidation zone. High moisture fuel can lead to the lowering of reactor temperatures and this in turn can inhibit the pyrolysis of the fuel. This will allow incompletely devolatised fuel to pass through the oxidation zone and hence result in tars passing through uncracked .

4.6.2 Scale-up limitations

Bridgwater et al., (1986) reported that the maximum throughput for downdraft gasifier is about 750 kg/h while Cogliali, (1986) reported that the maximum

throughput for a tar free operation is about 250 kg/h. The lack of scale up ability is mainly due to uneven distribution of oxygen (from the air injector) across the reactor. This will result in an uneven temperature distribution across the bed and hence result in a high tar content of the product gas (see section 4.4.1.1). As discussed earlier, one possible way to achieve better air distribution is to add more air injectors across the reactor. However, this could result in disturbances in the flow of solids through the bed which could further decrease the tar cracking ability of the gasifier.

In some literature the throughput of a downdraft gasifier is expressed as specific gasification rate which is the total dry fuel in kg/h that can be gasified per cross sectional area across the throat (Crane, 1979; Elliot, 1986; Graboski and Brogan, 1987). Alternatively it is also expressed as total dry volumetric gas flow per hour per cross sectional area across the throat. Downdraft gasifiers can only work within specific gasification rates. The specific gasification rate can range from 509-3900 kg/m^{2}h (Kjellstrom, 1989; William, 1989).

4.6.3 Reactor feeding

In order to prevent the leakage of pyrolysis and gasification products (such as carbon monoxide) from the gasifier and to prevent air from getting into the gasifier, the reactor will require an air-tight lid and sealed feeding device in order to avoid the risk of explosion or carbon monoxide poisoning (Bretherick, 1981; Reed and Das, 1988). The scale-up limitation of a throated downdraft gasifier is limited by the reactor feeding problems. Even though scaling up of a throated downdraft gasifier is limited, Groeneveld (1980) has reported a design of an annular throated gasifier with a capacity of 100 t/h. However, the system has not been built for actual trial.

4.7 GAS CLEANING FOR USE IN INTERNAL COMBUSTION ENGINES

The gas that leaves the gasifier contains contaminants such as tars and particulates. The tars are often present as a fine mist with droplet sizes in the submicron region and high temperature gases may contain tars in the vapour form. The particulates consists of char and inorganic ash. The quantities of tar and particulates present depends on the type of gasifier. The tar in the product gas of dense phase gasifiers before cleaning is

summarised in Table 4.6 (Brown et al., 1987; Esplin and McDonald, 1982; Jenkins, 1980; Graf, 1986).

Table 4.6
Tar and particulate contents in gasifier product gas before cleaning, mg/Nm^3

Types of gasifier	Tar content	Particulates content
Updraft	10000-100000	100-1000
Downdraft	500-1500	80-8000
Crossdraft (charcoal as fuel)	75-150	80-8000

The quantity of contaminants which can be accepted depends on the end use of the product gas. When the gasifier is close coupled to a combustion system, it may be possible to omit gas cleaning entirely. In the case where the product gas is used in internal combustion engines for power generation, the gas must be cooled and cleaned because of the following reasons (Baker et al, 1985):

a) To increase the volumetric efficiency of the engine because the power output is proportional to the absolute temperature of the air-gas mixture entering the engine. This implies that a high gas temperature will lead to a high loss in power.

b) To avoid corrosive wear and tear in the engine due to the presence of particulates.

The general agreement on the gas contaminants for producer gas engine systems is in the guide-lines by TNO, (1984) and is shown in Table 4.7.

Table 4.7
Permissible tar and dust content for engine

Contaminants	mg/Nm^3
Tar	< 50
Particulates	< 50

There are a number of field reports of different gas cooling and cleaning systems (Coovattanachai, 1986; Breag et al., 1982; 1985; Reines, 1988; Lemaitre, 1985; Sepalage, 1985). In general, the available gas cooling and cleaning equipment can be classified into two categories, namely:

1) Units not mechanically or electrically aided.
2) Mechanically or electrically aided units.

The first type is most commonly used in many developing countries for small scale units (Mendis et al., 1987; World Bank, 1985) because electricity or an external power source is not available. The most common non mechanically aided are cyclones, wet scrubbers and fabric filters. All of them, although commercially available are generally designed and fabricated locally using local material and expertise.

Mechanically or electrically aided units are used when the product gas is to be used to drive a turbine or for chemical synthesis and where water scrubbing will not be able to clean the gas properly. In most cases, electrostatic precipators are used (Bridgwater et al., 1986). These devices are physically large compared with other cleaning devices and require very high capital cost. They are therefore used only where very clean gas is required (Baker et al., 1985).

In this section, some past common gas cooling and cleaning systems commonly used in developing countries are reviewed.

4.7.1 Cyclone

Cyclone dust separators working on the centrifugal principle are popular because they are regarded as both cheap and reliable for the separation of bigger particles and have been frequently used. Kaupp, (1984) reported that a properly dimensioned cyclone can separate about 95 % of the coarse dust. However, the dimensions of the cyclone are only designed for a narrowly defined velocity range of the product gas and hence the gas volume flow per unit time has to be kept within a certain level. If the gasifier is not operating at full capacity (which in practice is often the case), the efficiency of the cyclone will drop significantly which will ultimately lead to clogging of the filters and other cleaning devices. Cyclones have the

advantage in that they can be operated at a high temperature. However, they are inefficient in removing particles of below 5-10 μm in diameter (Schulze and Leuchs, 1984; Hedden et al., 1985).

4.7.2 Wet Scrubbers

Wet scrubbers have been widely reported to be used in stationary as well as portable units. In almost all known uses, the wetting agent is water or oil (Kjellstrom, 1989; Bennett, 1981). Water scrubbing is normally used when water is readily available. The system used is a "once through" system which is in effect, a combined direct contact cooling and cleaning process. The gas flowing in the filter container is sprayed with water from above often through a packed bed of appropriate material (such as coconut fibre, coke, etc) to enlarge the effective surface area for cooling. However, it is the author's opinion that wet scrubbing in most of the reports is effective for charcoal gasifiers and generally caused further problems for wood gasifiers because tiny particles of carbon particles can pass through the scrubber untouched by water. Furthermore gasifiers using water systems usually have further filter problems as moisture and carbon can combine to block the filter creating a high pressure drop across the gasifier (Mendis et al.,1987; Knoef, 1991).

If oil is used for scrubbing, the pyrolytic oil from the gasification process is normally unsuitable because of its high contaminant content (Bailey, 1977; Calvert, 1972; Goss, 1980). The oil used must either be distilled before recycling or fresh oil must be used.

4.7.3 Fabric filters

A simple and very effective way of removing solid matter from the gas stream is the use of a fabric filter through a cloth or some other porous material. Some of the common fabric materials used are cotton, dacron and even fiberglass. Generally speaking, fabric filters have been very successfully used in most reported system (Coovattanachai, 1989). However, a major problem is the large pressure drop caused by condensation in the filter (Vasconselos and Furtado, 1985) and they are, therefore, not suitable as a filter for wood gasifiers.

4.8 DUAL FUEL ENGINE PERFORMANCE ON PRODUCER GAS

One of the most attractive applications of producer gas is its use in internal combustion engines such as the diesel engine with very little modification. Not all diesel engines are suitable for this type of conversion due to the compression ratios and the shape of the combustion chamber (Karim, 1966; 1980; Tiedema et al., 1983; Ogunlowa et al., 1979; Schumacher et al., 1984; Breag, 1981; Stassen and Van Swaaij, 1983). Diesel engines are manufactured in three types, namely:

1) Direct injection engines.
2) Turbulence chamber.
3) Ante chamber.

Direct injection engines, although they are working at high compression ratios compared with gasoline engines, are suitable and do not require a special low compression ratio as long as the compression ratio does not exceed 16 or 17 (Heynis and Ramackers, 1983). Turbulence and ante chamber engines are harder to convert because they have higher compression ratios (up to 21) and need to be reduced to 16 or lower. Nordstrom, (1962) reported that experiments conducted with engines of this type were very unsatisfactory and it was concluded that a major rebuilding of the engine was necessary in order to operate on producer gas.

The conversion of direct injection engine to dual fuel engine is well documented in a number of references (Anon, 1979; Giffen, 1944; Kanitkar, 1979; Ogunlowa, 1979; Weisgerber, 1980; Oritz et al., 1981; Mathur, 1981). During the conversion, all reports indicates power loss in dual fuel engines, typically 10-20 % of the original power on diesel (Heynis and Ramackers, 1983; Tiedema et al., 1983; Schumacher et al., 1984).

4.8.1 Diesel displacement

In dual fuel operation, a certain amount of diesel is necessary to ensure compression ignition of the producer gas air mixture and to ensure smooth combustion. This amount of diesel which is replaced by producer gas is often expressed as diesel displacement and this is the main purpose of dual fueling. It is expressed as the percentage of diesel displaced. There are

however considerable variations in diesel displacement. Vyarawalla et al., (1984) reported a diesel displacement of 75-85 % while Farcy et al., (1984) and Damour and Sabine, (1983) reported an average of 80 %. Cruz, (1984) reported an average of 77 % on half load and 63 % at full load. The wide variation in diesel displacement could be due to the different designs of combustion chambers. Nordstrom, (1962) suggested that the minimum diesel used is limited by its stable operation.

Diesel displacement is different from full load and partial load conditions (Alsthom-Atlantique, 1984; Coovattanachai, 1986; Goupillon, 1984). Under full load, it is the maximum amount of diesel that can be substituted, which is of greater interest. The maximum diesel substitution refers to a condition of no power loss under dual fuel operation. It is believed that the ultimate maximum limit of substitution is decided by the ignition requirement which is the minimum quantity of diesel required to ensure ignition. Any further decrease in the quantity of diesel will give rise to unstable or erratic running of the engine. Hence the maximum diesel displacement is limited for keeping the power capacity of the engine unchanged.

As mentioned earlier, a certain minimum quantity of diesel is necessary to ensure ignition and hence steady state operation. As engine load decreases, the usual procedure is to keep the diesel rate unchanged and to keep decreasing the supplementary fuel supply rate with changing load. This method of control is limited by the flammability limit of the supplementary fuel (Reed and Jantsen, 1979; Zerbin, 1983; Sharma and Chander, 1984). At lower loads when lesser and lesser amounts of supplementary fuel are introduced, the premixture becomes leaner and leaner until it finally reached a limit beyond which it is unable to support a flame. Reduction of supplementary fuel below this point implies the risk of the producer gas being exhausted unburnt. It therefore means that there is always a minimum load below which dual fuel operation should not be pratised.

4.8.2 Thermal efficiency on dual fuel

The thermal efficiency on dual fuel is defined as the percentage ratio of the total energy output (which is the power output for electricity production) to the total energy input from the supplementary fuel and diesel (Dennetiere et

al., 1980; Kjellstrom, 1980; Vyarawalla et al., 1984; Winterbone, 1983). The actual thermal efficiency depends very much on the timing and complete combustion of the premixed mixtures. At full load operation the premixed mixture is well above the flammability limit and therefore combustion is not a problem. As load decreases the premixed mixture become leaner and leaner and combustion becomes more difficult. Hence, a drop in efficiency is often reported (Tiedman et al., 1983; Ogunlowa et al., 1979; Dennetiere et al., 1980; Monford, 1982; Moore and Mitchell, 1955). There are many different values of thermal efficiency being reported in literature but most of these values are conditional than general because most of the engine loads are not stated.

4.8.3 Common problems of dual fuel engine performance on producer gas

Although producer gas engine systems have been used for a considerable period of time, a variety of problems have also been reported when producer gas is used for dual fueling. Rao et al., (1981) reported misfiring at lower load while Weisgerber, (1980) and Dennetiere et al., (1980) reported otherwise.

In terms of reliability of operation, Weisgerber, (1980) and Dennetiere et al., (1980) reported satisfactory performance while Kaupp, (1983) reported poor reliability. Breag et al., (1982) reported an increase in the base number and heptane insolubles in lubrication oil. Parikh et al., (1983) , Vyarawella, (1984) reported serious deterioration of lubricating oils and increased presence of phenolic compounds. They also reported problems related to the presence of tars such as sticking of valves, sticking of piston rings in the grooves and carbon deposits on the piston head and combustion wall chamber. Breag et al., (1982) and Shilton, (1983) also reported such tar deposition and related problems.

4.9 TURNDOWN OF DOWNDRAFT GASIFIER

In commercial applications of gasifier-engine systems such as for shaft power and electricity production, the gasifier system must be able to respond to varying load changes and therefore must have some turndown capability. Turndown can therefore be defined as the ability of the gasifier to respond to

changes in demand for product gas at wood capacity and at the same time be operated with a stable reaction zone.

The turndown percentage is defined as the ratio of the dry wood capacity to the maximum dry wood capacity of the gasifier. The maximum dry wood capacity is the maximum throughput at which the gasifier can be operated with a stable reaction zone. This maximum throughput is highly dependent on feed properties such as shape, size, moisture content and air factor. The turndown percentage is defined as:

$$\frac{\text{Dry wood capacity}}{\text{Maximum dry wood capacity for stable operation}} * 100$$

Turndown is sometimes expressed as a ratio known as turndown ratio.

Turndown ratio is defined as:

$$\frac{\text{Maximum dry wood capacity for stable operation}}{\text{Dry wood capacity}}$$

Reed, (1981) discussed the need for turndown to be included in measurements and specifications because this property is required for load varying applications. He also reported that fixed bed and fluidised bed gasifiers have typical turndown ratios of 5 (or 20 %) and 2 (or 50 %) respectively. However, no reliable information was found in the literature on turndown ratios of established systems. In this research, the phenomena of the turndown in a throated downdraft gasifier is investigated.

CHAPTER 5

GASIFIER DESIGN, OPERATION AND EXPERIMENTAL PROCEDURE

5.1 INTRODUCTION

The main objective of this research is to investigate the performance of a rubberwood gasifier and engine with electricity generation. The gasifier is also used to collect basic research data to assist in the future implementation and dissemination of the technology in Malaysia. This chapter describes the design and fabrication of the downdraft gasifier as well as the experimental procedures used in procuring experimental data for analysis.

The rubberwood gasifier that is to be fabricated was meant for dissemination and use in rural areas of Malaysia and hence the main emphasis is simplicity in design and operation. Because this is the first wood gasifier to be built in Malaysia, there was very little information on the suitability of materials and design systems. As a result a large portion of the design features and material used had to based on field experiences and reports from other countries with similar operating conditions.

5.2 RUBBERWOOD GASIFIER-ENGINE SYSTEM

5.2.1 Gasifier design

The maximum electrical output of the gasifier was constrained by the availability of a suitable engine to be converted to dual fuel. The most commonly used diesel engine in the rural areas of Malaysia is the Lister HR2 diesel engine. This engine is chosen for the research because of its proven reliability and the familiarity of operating this type of engine by the rural population.

The maximum electrical output of the HR 2 diesel engine according to the local engine supplier is 40 kWe. Based on an average power derating of

12.5 % on dual fuel for an engine of of this size, the gasifier was therefore designed on the basis of a maximum 35 kWe power (Coovattanachai, 1989).

Humphrey (1985) who had successfully used Lister engines of Model HR3 reported an average thermal efficiency of 15-25 % when operated on dual fuel. Since Model HR3 is an updated version of Model HR2 it is assumed that both models will have similar thermal efficiency. In order to determine the maximum wood input, a minimum thermal efficiency is used. Hence,

Maximum thermal energy of the wood = 35 kW/0.15
= 233.3 kW or 233.3 kJ/s.

The average higher heating value of rubberwood is 18436.5 kJ/kg (see chapter 6).

Thus, the maximum wood input on a dry basis = 233.3/18436.5 kg/s
= 0.0127 kg/s
= 45.56 kg/h

From Table 6.1, the average moisture content of rubberwood is 7.9 % (wet basis).

Maximum weight of wet rubberwood input = 45.56/(1-0.079) kg/h
= 49.5 kg/h

Coovattanachai (1989) reported that the specific air requirement to gasify tropical hardwood is 2.5 Nm^3/kg of wood with a moisture content of 15 % (wet basis).

Hence the maximum air requirement = 2.5 * 49.5 Nm^3/h
= 123.7 Nm^3/h

Taking the average operating temperature in Malaysia to be 32°C, the maximum volume of air required at normal operating temperature in Malaysia is:

123.7 * 305/273 = 138.2 m^3/h

For a gasifier of similar capacity, Nordstrom (1962) reported that the gasifier has to be operated with an inlet air injector velocity of 30-35 m/s.

Taking the maximum air jet velocity to be 35 m/s, then the volume of air supplied by the nozzles per second is given by:
Total aperture area of nozzle * Maximum air injector velocity
Thus the total aperture area of the nozzles $= 138.2 / (60 * 60 * 35)\ m^2$
$= 0.00109\ m^2$

Assuming that air input is to be distributed by 3 nozzles as proposed by the Swedish Experience (Anon, 1979), the cross sectional area of each nozzle is:

$0.00109/3\ m^2 = 0.00036\ m^2$
Hence the diameter for each nozzle $= 2.1$ cm

The minimum permissible specific gasification rate for a classical Imbert type of throated downdraft wood gasifier was reported to be 0.35 Nm^3/cm^2h (Skov and Papworth, 1975) across the cross sectional surface area of the throat.

In order to determine the maximum gas production of a gasifier, it is assumed that the air/product gas requirement is 1.1:1.0 for a producer gas system (Kaupp and Goss, 1981).

The maximum volume of gas generated $= 123.7/1.1\ Nm^3/h$
$= 112.5\ Nm^3/h$

Thus, using the specific gasification rate to be 0.35 Nm^3/cm^2h,
Surface area of throat is $112.5 / 0.35 = 321.4\ cm^2$
Hence, throat diameter is $\sqrt{321.4 * 4/3.142} = 20.2$ cm

From the design guide-lines of downdraft gasifiers given by the Swedish Academy of Engineering Sciences (Anon, 1979), the diameter of the throat (D_t) at depth h below the air nozzle is given by:

$$\frac{h}{D_t} = 0.75$$

where
h = depth of throat below the nozzles
D_t = diameter of the throat
Hence,
$h = 0.75 * 20.2$ cm
$= 15.2$ cm

Venselaar (1982), compared the design characteristics of a number of gasifiers that were commercially available during the Second World War. He suggested that the height of the reduction zone (see section 4.4 of Chapter 4) for throated gasifiers should be more than 20 cm. For a nozzle blast velocity of around 30-35 m/s, using wood blocks of dimensions 3 cm x 6 cm x 8 cm, Venselaar recommended a reduction zone of 30 cm. This dimension was used in the gasifier design.

To facilitate good fuel flow inside the reactor, for a classical throated gasifier built by Imbert (1985), the specific gasification rate was 300 kg/m^2h across the cross sectional area of the gasification zone.

Hence the area of the gasification zone is given as:

$$49.5 / 300 \text{ m}^2 = 0.165 \text{ m}^2$$

Hence, the diameter of the gasification zone = 45.8 cm
The diameter of the oxidation zone is therefore taken as 45 cm. To enable wood to flow through the oxidation zone the diameter of the reactor was fixed at 55 cm.

The maximum wet wood input of the gasifier is 49.5 kg/h. In order to reduce excessive air leaking into the gasifier during fuel feeding, the upper fuel bunker of the gasifier is designed to hold between 55-60 kg of wood so that a full load of wood will last for at least one hour and the feeding frequency can be reduced. The average bulk density of rubberwood was found to be 289.1 kg/m^3 (see section 6.1 of chapter 6). For a maximum load of 60 kg of rubberwood, the maximum volume of the fuel bunker will be:

$$60/289.1 \text{ m}^3 = 0.20 \text{ m}^3$$

By taking the diameter of the gasifier to be 55 cm (see earlier calculations), the height of the fuel bunker is therefore $= 0.20 * 4/(3.142 * 55 * 55)$

$= 84$ cm.

Wood is designed to feed into the fuel bunker via a hopper mounted at the top of the reactor. The hopper has a gate valve at the base which can be manually opened to allow wood to flow into the fuel bunker of the reactor. To reduce excessive heat losses from the gasifier, an additional outer

annular cylinder was built to allow for some preheating of incoming air and some cooling of the product gas. The distance separating the two cylinders was chosen as 7.5 cm in order to allow sufficient volume for the product gas and incoming air to have effective heat transfer during the gasification process (see Figure 5.1 and 5.2).

The oxidation zone is connected by six horizontal nozzles of which only three of the nozzles were used as air inlets for most of the experiments while the remaining three are fitted with observation ports to observe the behaviour of the wood particles in the oxidation zone. All the nozzles are arranged radially at equal distances above the throat. The nozzles are made of short pieces of mild steel cylinders with an internal diameter of 2.1 cm. The outer end of the nozzles were internally threaded so as to allow the individual nozzles to be blocked when necessary. When three nozzles are used during the runs, the alternate nozzles were blocked by the use of an end-cap with observation glasses fitted on it.

Air is introduced into the gasifier through the nozzles via a single air inlet port situated on the top of the reactor. The air inlet pipe had a 8.89 cm gate valve (V_1 on Figure 5.7 and 5.8) which could be opened to allow air into the gasifier during the runs or closed to seal off the gasifier at the end of the run.

The oxidation reduction zone was insulated with a 5 cm thick high temperature refractory cement in order to achieve a high reaction temperature and reduce the erosion of the air nozzles due to oxidation. Because of the relatively wide diameter of oxidation zone and the presence of refractory cement, a heavy cast iron throat will not be suitable as the refractory will not be able to support its weight. It was decided therefore to use some other lighter material. An Indian deep oil curved frying wok was chosen as a trial because of its ability to withstand high temperature. The two side handles of the wok are carefully bent to allow it to be used as a support to help anchor the throat in the correct position in the gasifier. Before the wok was installed inside the gasifier reactor, a throat diameter of 20.2 cm was carefully cut in the centre of the wok by a professional cast iron manufacturer. It was however not an easy task and 15 woks had to used before the correct dimension was finally obtained and installed. Plate 5.1 shows the complete unit

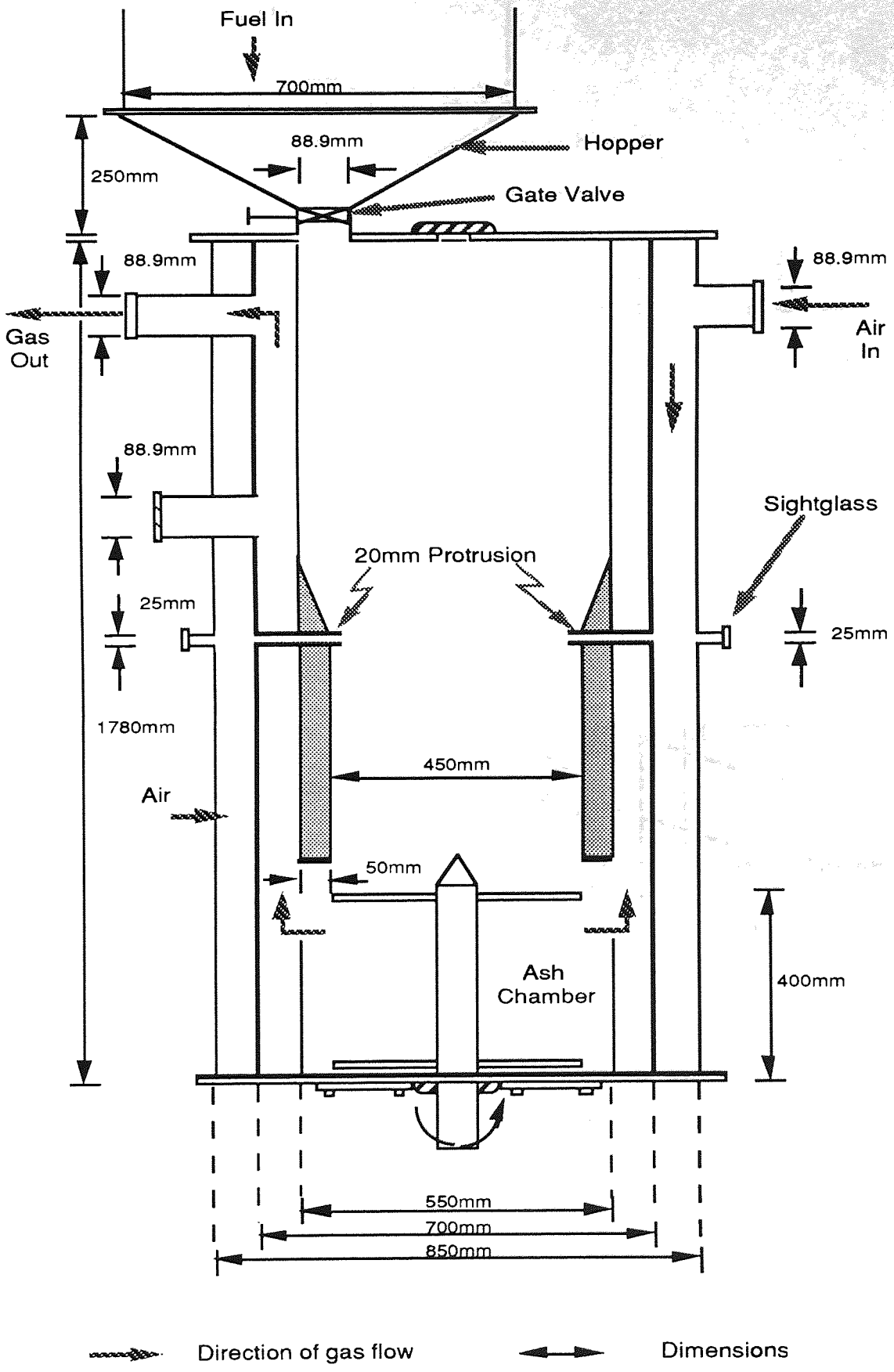


Figure 5.1 Gasifier plan without throat

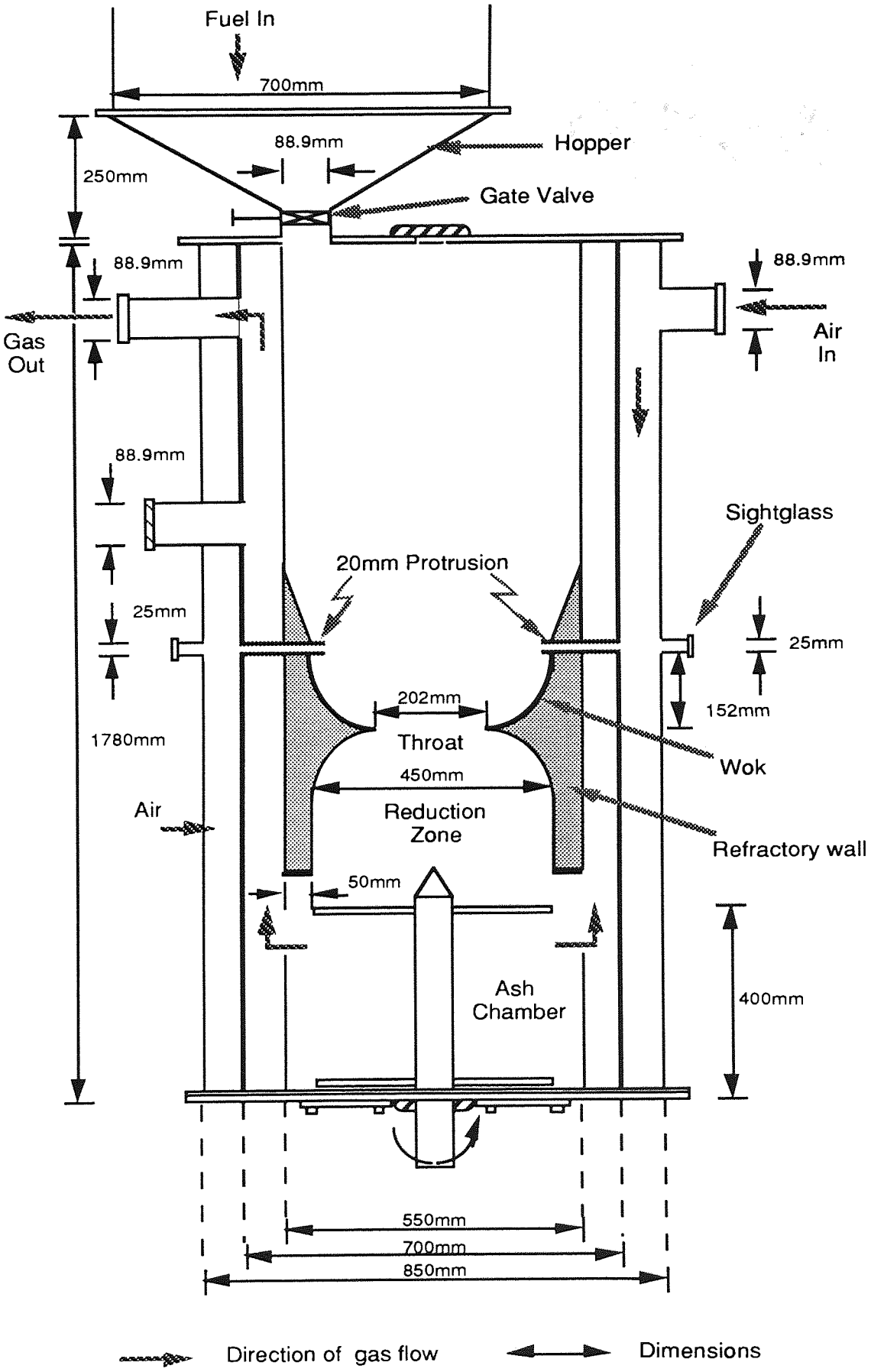


Figure 5.2 Gasifier plan with throat

Plate 5.1 Gasifier unit at Forest Research Institute of Malaysia.

Below the reduction zone is a rotating mild steel grate which allowed the removal of ash, char and dust by turning the vertical axial shaft into the ash chamber. The ash chamber was 40 cm deep to allow sufficient volume for the accumulation of ash, dust and char obtained during the gasification process. Ash, dust and char particles collected in the ash chamber are removed by opening the two access doors located at the lower part of the gasifier. The exact design and dimensions of the gasifier before and after the throat was installed is shown in Figure 5.1 and 5.2 respectively.

5.2.2 Gas cleaning and cooling

The gas leaves the gasifier at a temperature of between 250-300°C and is loaded with dust, pyrolytic products and water vapors. It is necessary to cool and clean the gas in order to remove as much water vapor, dust and pyrolytic products as possible from the gas before it enters the engine. The gas cooling and cleaning equipment used for this research are described below.

5.2.2.1 Drum cooler

The initial design was a drum cooler to cool the hot product gas as quickly as possible as it emerged from the gasifier. This method is based on the design used in the Imbert gasifiers (Imbert, 1985). The condensation drum is a cylindrical vessel with a diameter of 60 cm and a height of 90 cm. The drum is connected by a 8.89 cm diameter inlet pipe positioned 20 cm from the circumference of the top plate of the drum. The gas outlet pipe, 8.89 cm in diameter is located at the centre of the drum cooler. The drum cooler is fitted with a ball valve for draining condensates that accumulate. To prevent excessive pressure built-up in the drum cooler, a safety valve is also installed at the top of the drum cooler. The design and dimensions of the drum cooler are shown in Figure 5.3.

5.2.2.2 Cyclone dust separator

After 73 runs, it was decided that a cyclone dust separator be installed in place of the original drum cooler with the objective of improving the gas cleaning process. There were, however only a few industrial cyclone

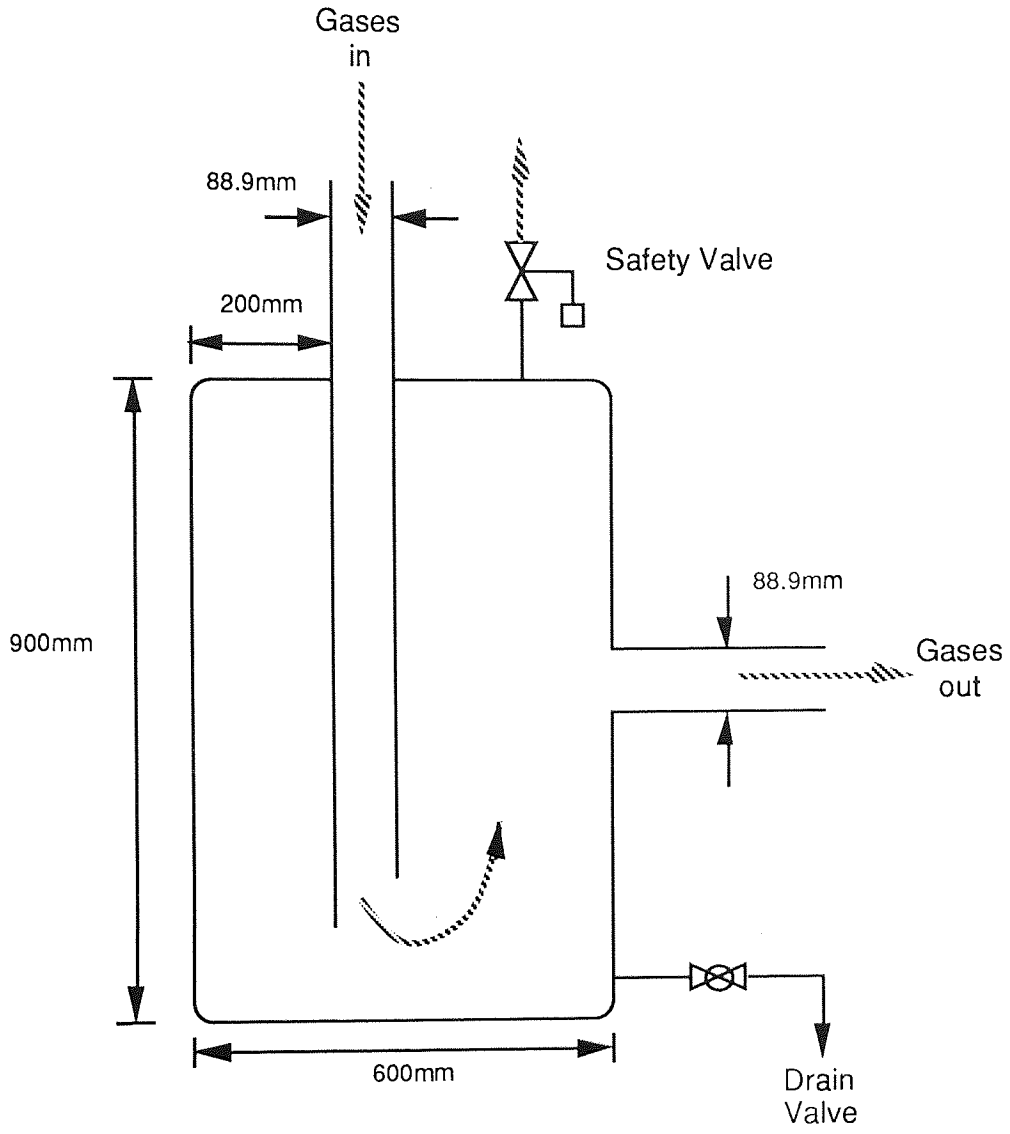


Figure 5.3 Drum cooler

manufacturers in Malaysia who were familiar with fabricating cyclone dust separators designed to remove particles from producer gas.

There are many field reports on the use of cylone dust separators installed on gasification units (Anon, 1979; Canese, 1987; Graf, 1985; Hollingdale, 1983; Stairmand and Kelsey, 1955; World Bank, 1986). Of the many field reports, the dimensions and geometric configuration of the cyclone used by Gasgene in Paraguay was chosen because it fitted best with the power output capacity of the experimental gasifier (Canese, 1987). Entrained char and dust particles are collected at the cyclone dust chamber located at the base of the cyclone.The design and dimensions of the cyclone are shown in Figure 5.4. The cyclone dust separator was used for runs 74-101.

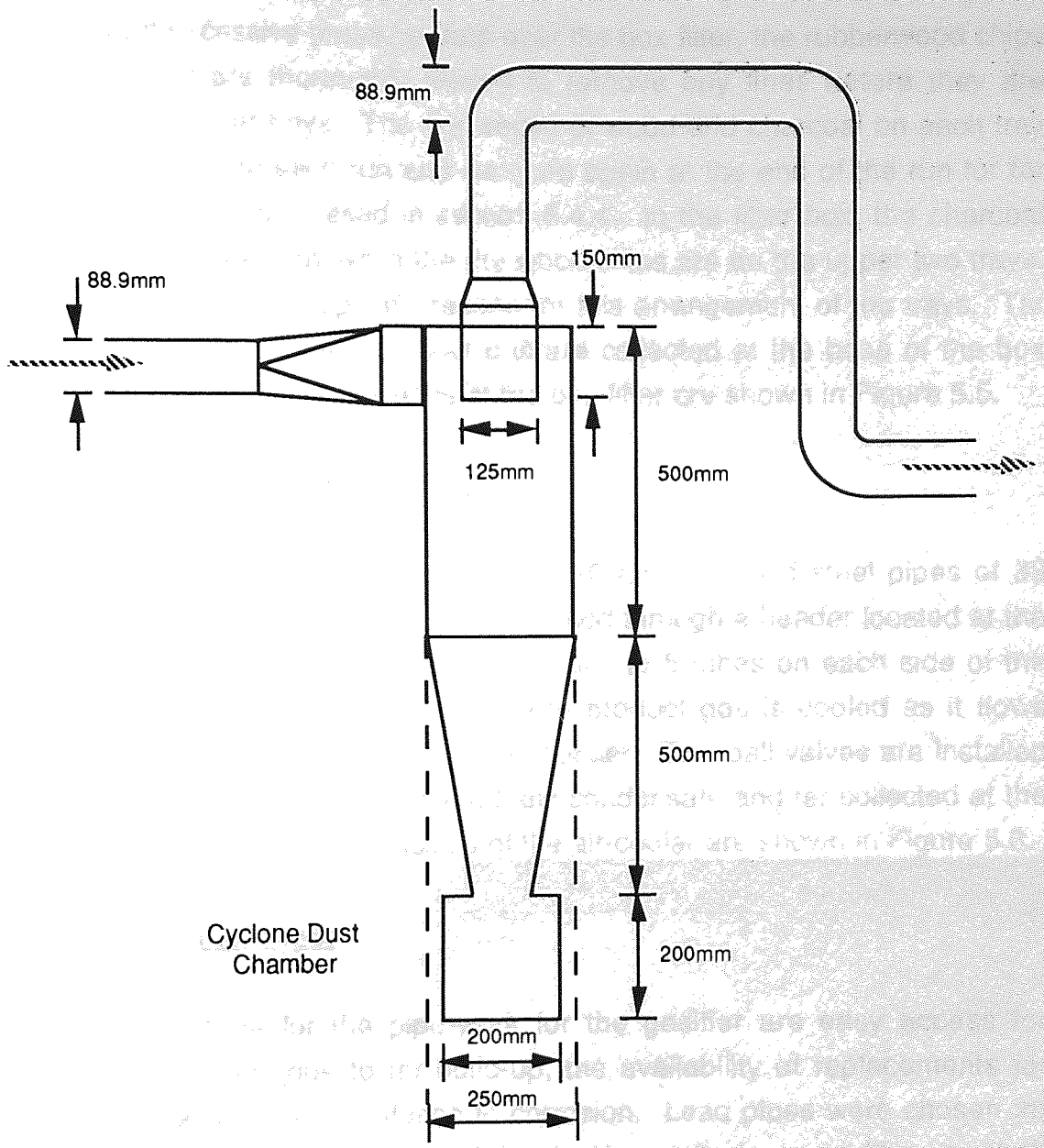


Figure 5.4 Cyclone dust separator

5.2.2.3 Box filter

After the initial drum cooler or the replacement cyclone dust separator, the product gas passes through a vertical box filter. The box filter has three layers. Wood and charcoal are chosen as the filter medium so that the contaminated filter can be reused as fuel later. The size of rubberwood chips chosen as filter medium is 1 cm x 1 cm x 1 cm while the rubberwood charcoal filter used is between 1-2 cm in size. For every run only dry (< 5 % moisture on wet basis) and clean rubberwood chips and charcoal are used.

To prevent excessive pressure drop over the box filter, the rubberwood chips and charcoal are thoroughly sieved to remove any fines before they are placed in the filter trays. The dry weight of wood and charcoal on each tray is recorded before each run and weighed again at the end of the run for tar determination as discussed in section 5.4.4. In the filter box, the charcoal occupies the lower tray while the dry wood chips are on the upper two trays. There is, however, no specific reason for this arrangement of the trays. Tar and condensate from the product gas are collected at the base of the box filter. The design and dimensions of the box filter are shown in Figure 5.5.

5.2.2.4 Air-cooled condenser

The air-cooled condenser was made of 10 tubes of mild steel pipes of 38 mm diameter. The product gas is introduced through a header located at the bottom of the cooler that distributes the gas to 5 tubes on each side of the double pass air-cooled condenser. The product gas is cooled as it flows through the tubes in the air-cooled condenser. Two ball valves are installed at the base of the cooler to drain off any condensate and tar collected at the base. The design and dimensions of the air-cooler are shown in Figure 5.6.

5.2.2.5 Pipe-work

The three criteria for the pipe-work for the gasifier are easy access for cleaning the pipes due to tar build-up, the availability of replacements for any modifications and resistance to corrosion. Lead pipes were chosen for the pipe-work because they satisfy all three criteria in addition to their relative abundance in Malaysia. The diameter of the pipe chosen was a standard 8.89 cm. Tar cleaning in the pipe can be done by inserting a specially designed scraper inside the pipe to remove the tar deposits condensed on the inside of the pipe. Along the pipe-work were also fitted a number of gate valves to regulate the gas flow in the gas cleaning and cooling system. The locations of the gate valves are illustrated in Figure 5.7 and 5.8.

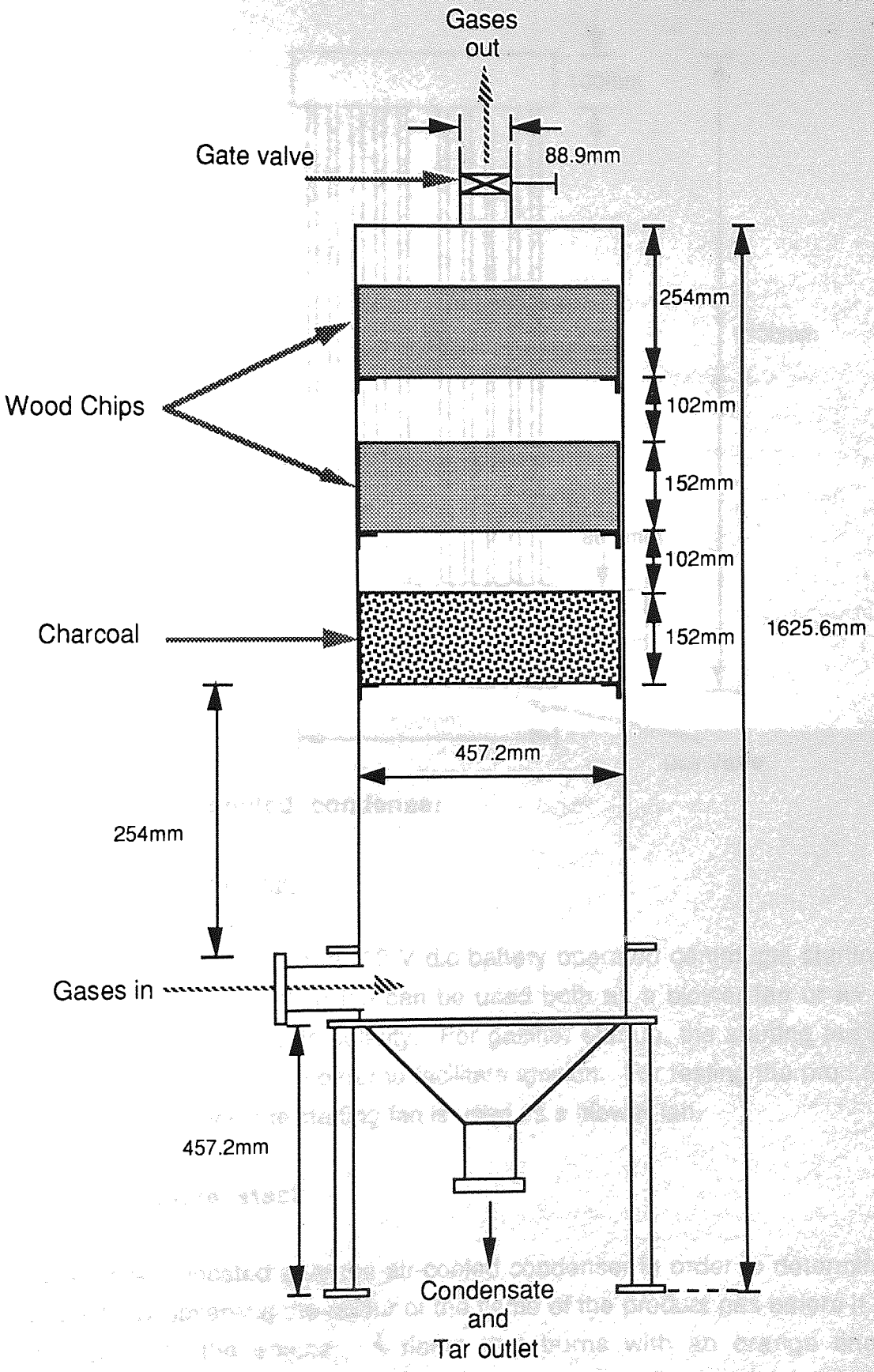


Figure 5.5 Box filter

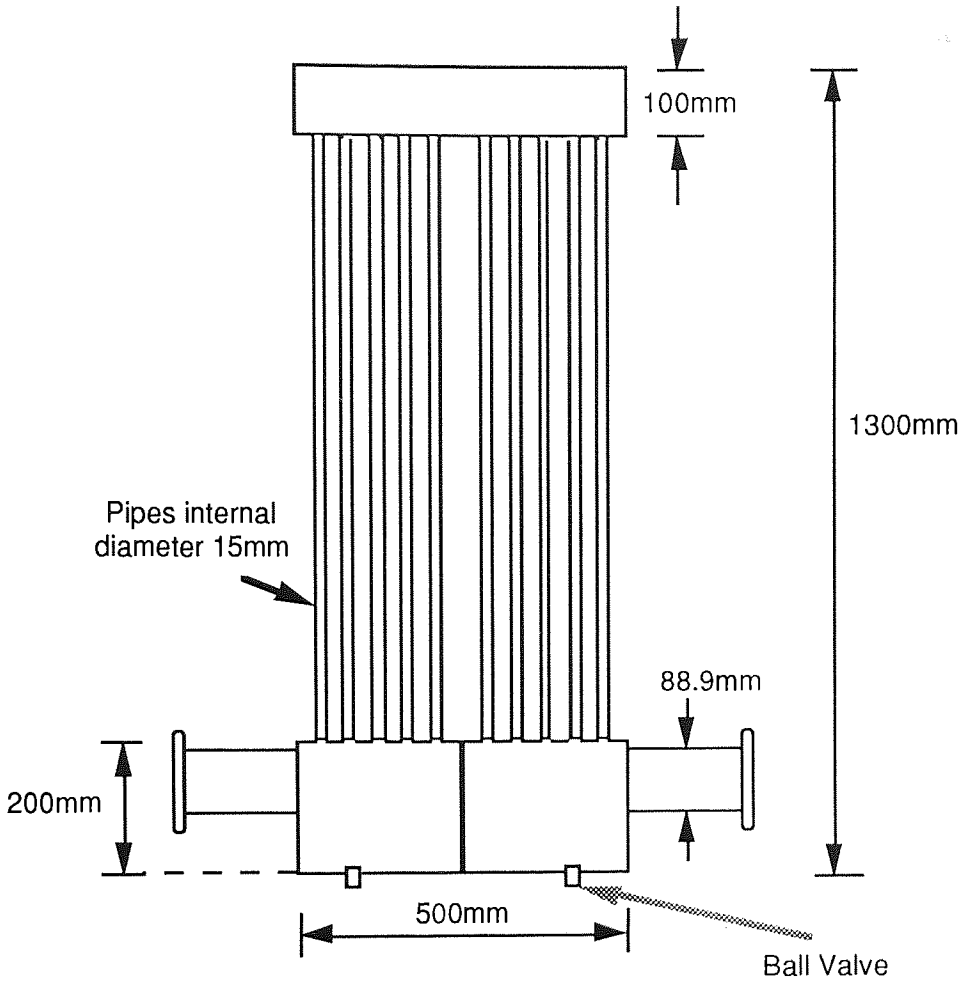


Figure 5.6 Air cooled condenser

5.2.2.6 Starting fan

For starting up the gasifier, a 12 V d.c battery operated centrifugal starting fan was used. The starting fan can be used both as a blower fan or as a suction fan by reversing its polarity. For gasifier startup, the starting fan is used as a suction fan to in order to facilitate ignition. For testing the product gas at the flare stack, the starting fan is used as a blower fan.

5.2.3 Flare stack

A flare stack is located after the air-cooled condenser in order to determine the quality by observing the colour of the flame of the product gas before it is introduced into the engine. A flame that burns with an orange tinge indicates the presence of a high quantity of tar in the product gas while a transparent pale blue colour indicates the gas is suitable for introduction into

the engine (Anon, 1979). The flare stack is a simple pipe with a stainless steel flame trap mounted on top of it. The product gas emitted from the flare stack is ignited by the use of household matches or by a burning wick dipped in diesel.

5.2.4 Air-gas mixer and engine specification

5.2.4.1 Air-gas mixer

The air-gas mixer is in the form of a simple T junction where the air flow can be manually adjusted to mix with the product gas before the mixture is introduced into the engine. Due to different objectives of the experimental design listed in Table 6.10, the air-gas mixer has to be constantly adjusted in order to achieve a steady power output of the gasifier.

Although the design is simple, it is an effective way to control the power output as soon as the operator is familiar with its operation.

5.2.4.2 Diesel engine

The engine used for the trials is an unmodified diesel engine with the specifications listed in Table 5.1.

Table 5.1
Specifications for Lister HR2 engine

Engine		**Alternator**	
Bore	107.95 mm	Model	ECC series model BRF 225
Stroke	114.30 mm	Output	max 40 kW
Displacement	2090 c.c	Load	resistive
Compression ratio	16:1	Voltage	440V
Speed	1200 - 2200 rpm		
Number of cylinder	2		

5.2.5 Gasification system layout

The complete gasification unit layout is illustrated in Figure 5.7 with the original drum cooler, and Figure 5.8 after replacing the drum cooler with a cyclone dust separator. Plate 5.2 shows the air-gas mixer and the throat.

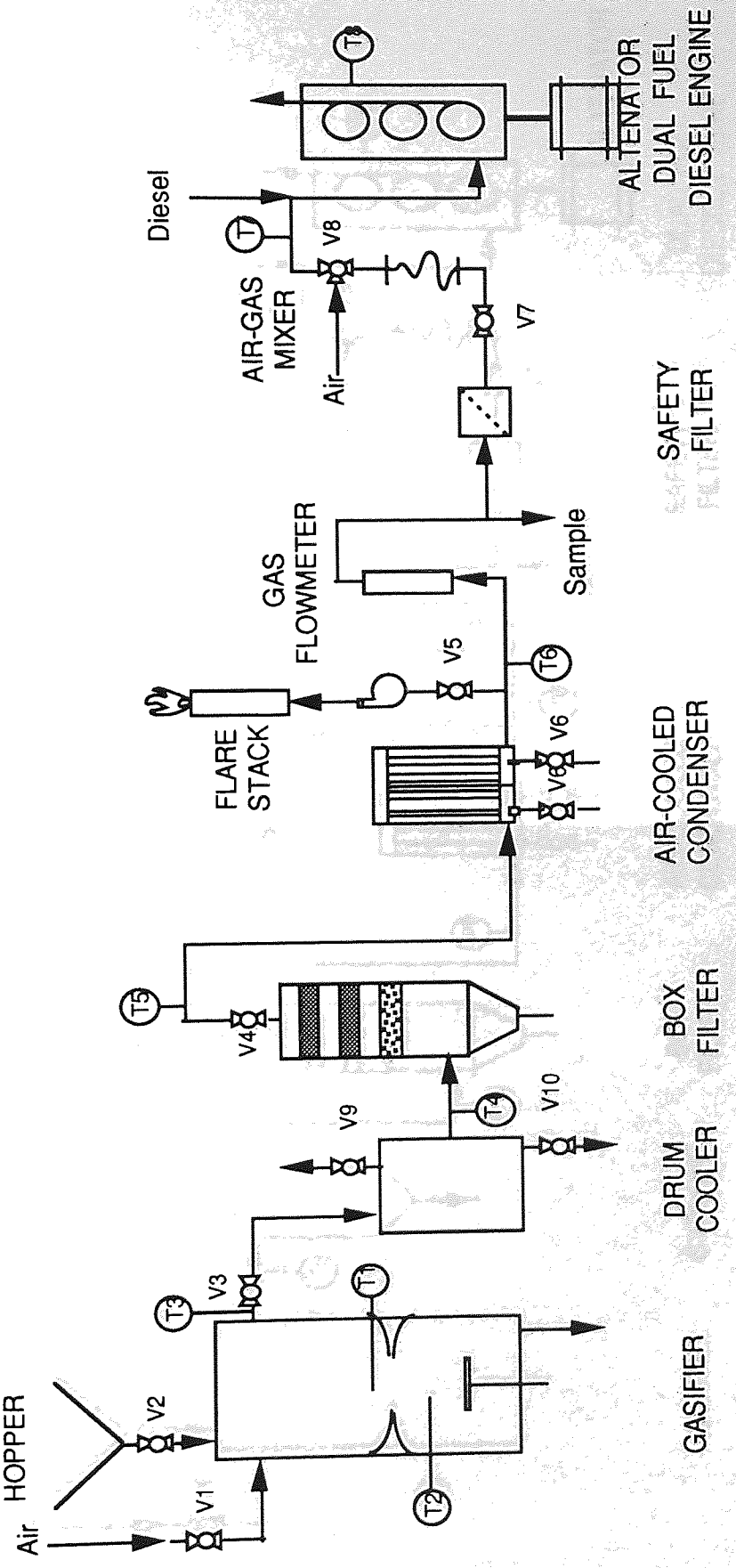
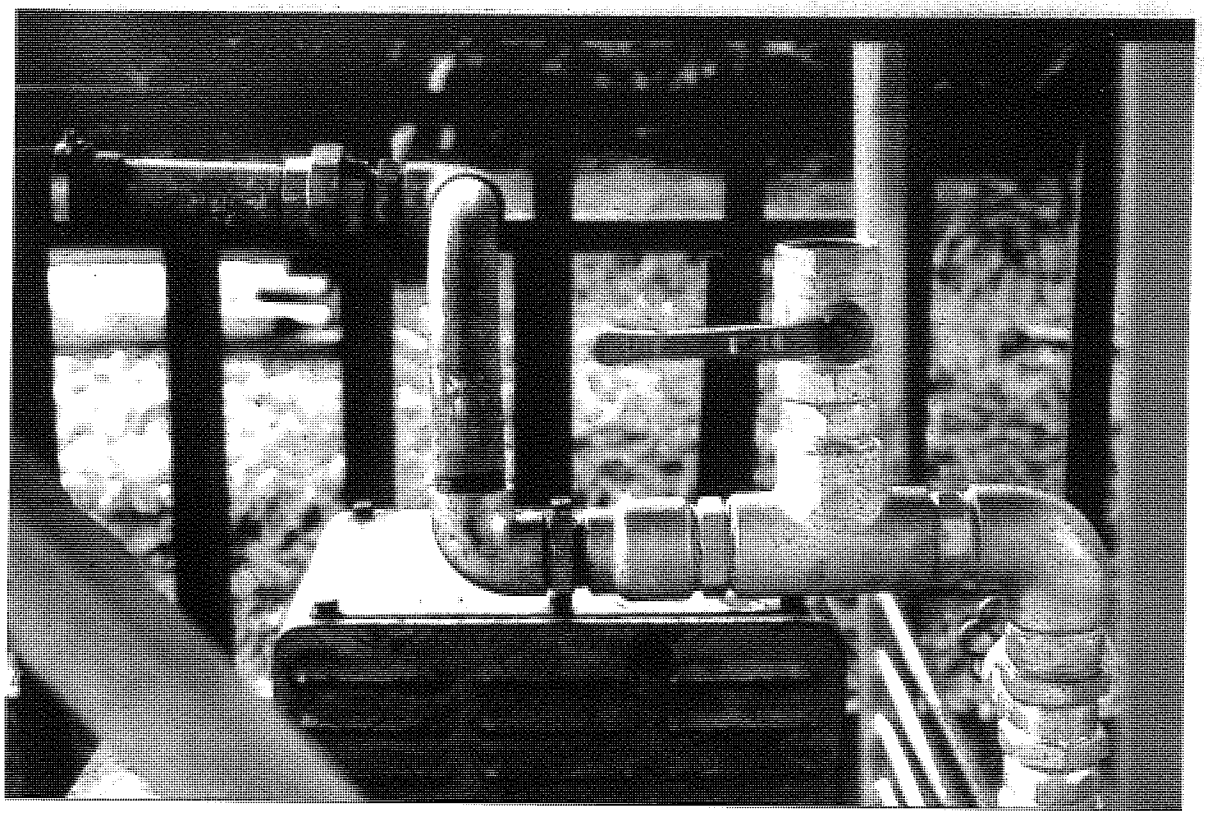


Figure 5.7 Gasification system layout BEFORE modifications



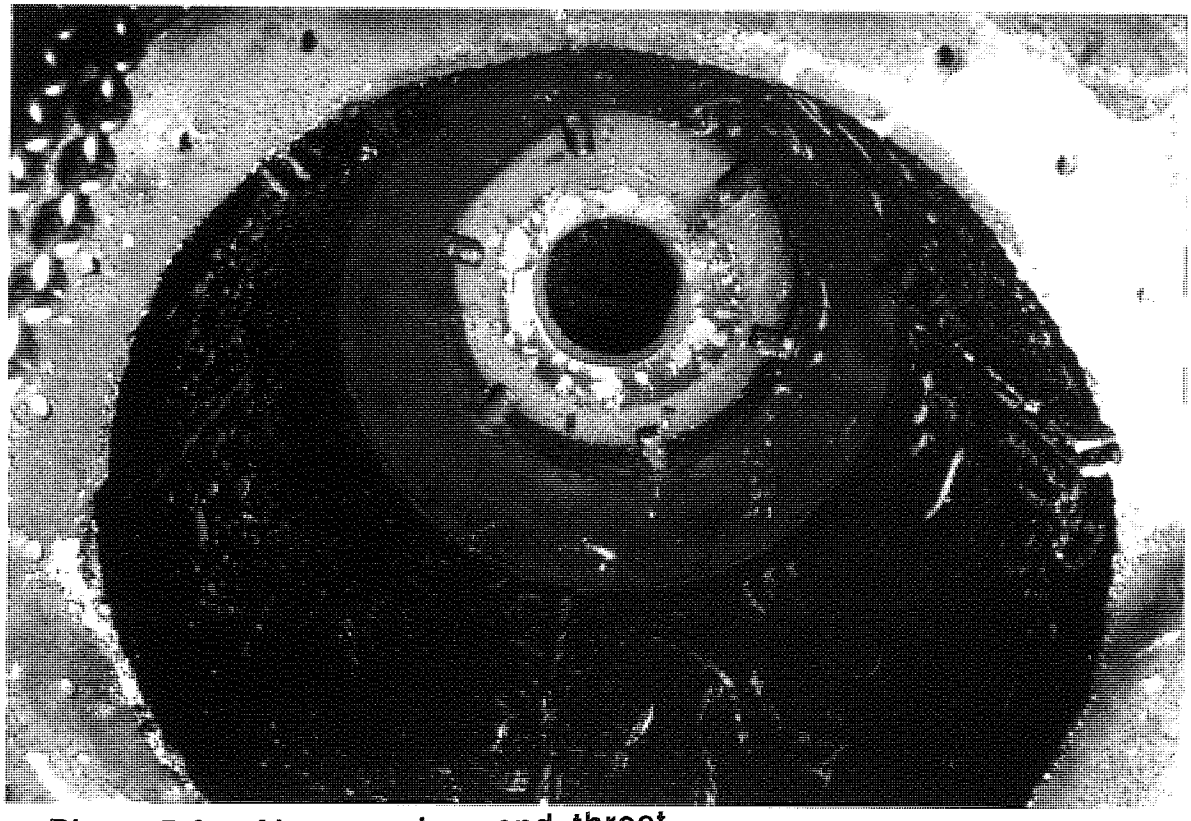


Plate 5.2 Air-gas mixer and throat

5.3 OPERATION OF THE GASIFIER

The operation of the gasifier can be divided into four parts:

1) Start-up, which includes all operations required until a steady state, whereby the power output of the engine is stable is reached.
2) Gasifier operation, which includes all the data to be collected as soon as the gasifier is in steady state. The data collected are the wood flowrate, gas flowrate, gas composition analysis, diesel flowrate, power output, temperature and pressure measurements (see section 5.4).
3) Shut-down procedure, which includes all the actions to safely seal the gasifier.
4) Clean-up, which includes all the procedures required to collect tar, char, ash and condensate for mass and energy balance analysis.

5.3.1 Start-up procedure

An hour prior to start-up, the following steps are carried out:

a) The bottom plate of the gasifier is bolted back. Check all the pipe-work joints and access doors at the ash chamber, cyclone dust chamber and the tar and condensate collection port of the filter box are all securely tightened.
b) Check all wiring connections in the gen-set.
c) The starting fan to be used as a suction fan is then mounted onto the flaring stack of the gasifier.
d) To ensure that the gasifier can be lighted up easily, about 0.5 kg of fresh and dry charcoal is first loaded into the gasifier through the hopper.
e) Preweighed batches of wood chips are then carefully loaded into the gasifier until the wood chips filled up to a predetermined level.
f) Preweighed clean and dry wood chips and charcoal for use as filters are placed in the respective trays in the box filter.
g) The engine is checked to ensure that it is in operational condition.
h) The diesel tank is filled with diesel to a predetermined mark.
i) All the valves positions are checked against the list in Table 5.2.

Plate 5.3 Colour of flame during start-up

5.3.2 Gasifier operation

After lighting up, the gasifier was then operated until all the objectives of the individual runs summarised in Table 6.10 were achieved. However, due to the high tar production during start-up, the various parameters for each run are only measured after 15 to 20 minutes of steady state operation. The parameters measured (see section 5.4) for each run are summarised in Table 6.11.

5.3.3 Shut-down procedure

Once all the objectives of each experimental run had been met, the gasifier could then be shut down. The shut-down procedure is follows:

1) Before shutting down the gasifier, wood chips are added to the gasifier until the initial predetermined level during start-up is reached.
2) The engine is stopped.
3) Valves V1, V2, V3, V4, V7 and V8 are closed.
4) The gasifier is allowed to cool by itself overnight so that it will be sufficiently cooled and safe to open up the next day.

5.3.4 Clean-up procedure

When the gasifier is sufficiently cooled, the following steps are taken:

1) The access door at the ash chamber is opened and all the ash and char are carefully collected.
2) The bottom plate of the gasifier is opened and more ash and char are carefully collected.
3) The top plate of the gasifier is opened so that all unused wood chips in the gasifier are carefully removed.
4) For runs 22-73, the valve V10 in the drum cooler is then opened and all the condensate is carefully collected. For runs 74-101, the cyclone dust chamber is removed and all the char and ash is collected.
5) The three filter trays are removed from the filter box and the contents weighed.
6) All the char, ash and condensate in the filter box are collected.

7) Valve V6 is opened and all the condensate is drained from the air-cooled condenser.
8) The gasifier is then thoroughly cleaned by hand with the use of a specially designed scraper.
9) After cleaning the gasifier, all the removable parts were fitted again.
10) During the fitting process, all the gaskets were carefully checked and replaced if necessary. The gasifier is then ready for the next run.

5.4 EXPERIMENTAL PROCEDURE

In order to determine the mass and energy balances, a number of physical and chemical properties of rubberwood have to be known. Before the wood is analysed, chips of various sizes were prepared and characterised by the method described below in section 5.4.1.

5.4.1 Preparation and characterisation of rubberwood

Rubberwood (*Hevea brasiliensis*) is a hardwood and samples were obtained from the plantations of the Rubber Research Institute of Malaysia located at Sungai Buluh, the outskirts of Kuala Lumpur. 30 year old mature trees were chosen for the research. For ease in transporting the trees back to the laboratory, the trees were cut into 2 m long logs. At the laboratory, the logs were first debarked and then cut into 3 cm x 3 cm thick planks by the use of a table saw. To investigate the effect of particle size on the gasification process, the wood are chipped into six different sizes by adjusting the cutting knives of the Taihei wood chipper from 1 cm to 6 cm. The average wood size is then classified by passing them through a series of vibrating sieves of a Kumegai Riki Chip Classifer where wood of sizes smaller than 3 cm x 3 cm x 1 cm or greater than 3 cm x 3 cm x 6 cm were sieved out. The wood is classified as follows:
3 cm x 3 cm x 1 cm
3 cm x 3 cm x 2 cm
3 cm x 3 cm x 3 cm
3 cm x 3 cm x 4 cm
3 cm x 3 cm x 5 cm
3 cm x 3 cm x 6 cm
Plate 5.4 shows the rubberwood used as feedstock in the project.

Plate 5.4 Rubberwood used as feedstock

The advantage of the Taihei wood chipper in wood chip preparation is that it gives a uniform particle size distribution and little time is required to supervise it. Furthermore wastage is kept to a minimum level.

5.4.2 Determination of physical properties of rubberwood

5.4.2.1 Absolute density and bulk density determination

Four samples of each wood size (altogether 24 samples) were chosen randomly for absolute and bulk density analysis. A cylindrical wood piece was cut out from each test sample with the help of a hole saw of diameter 19 mm. The actual dimensions of each piece were measured with the aid of a micrometer. With the dimensions, the volume of each wood sample can then be determined. The wood samples were then dried to a constant weight at 103 °C in a ventilated oven for 24 hours. The weights of the oven dried samples were then recorded. The absolute wood density was calculated as (BSI, 1973):

$$\text{Absolute wood density} = \frac{\text{weight of dry wood}}{\text{volume of wood}}$$

The bulk density of the samples was determined by filling a two litre measuring cylinder with four samples of each wood size (24 altogether). The measuring cylinder was tapped gently until the sample investigated was well settled in the cylinder. The bulk density was calculated as:

$$\text{Bulk density} = \frac{\text{weight of dry wood}}{\text{volume of measuring cylinder}}$$

The average values of the absolute and bulk density are summarised in Table 6.1.

5.4.2.2 Moisture content

The moisture content (MC) of each of the samples was determined by normal ASTM Standards D-3175-85. Wood samples were dried in a ventilated oven at a temperature of 103°C until a constant weight was obtained. The MC was determined by the following relationship:

$$MC = \frac{\text{green weight - oven dried weight}}{\text{green weight}}$$

The moisture content is thus expressed in the wet basis form. The results are tabulated in Table 6.1.

5.4.3 Chemical properties

5.4.3.1 Chemical composition, proximate and ultimate analysis

Four samples of each wood size were sent to the Rubber Research Institute of Malaysia for the chemical, proximate and ultimate analysis. The results of the analysis are presented in Appendix 6.1. The mean values of the analysis are summarised in Table 6.2, Table 6.4 and Table 6.5.

5.4.3.2 Higher heating value (HHV)

The higher heating value of rubberwood was determined by the Adiabatic Bomb Calorimeter Model Parr-1241, Parr Instrument Company, USA. The standard used is the ASTM D2015-77 method with a slight modification. Instead of the standard pelletised samples, solid wood samples were used. This is because the the pelletised samples tended to disintegrate when the samples were placed in the bomb of the calorimeter. Tan and Scott (1989) reported that there was in fact no significant difference in the calorific value of wood in either using 'solid' or pelletised samples. As a check on the accuracy of the determination, the higher heating value was also calculated by the by the IGT equation (IGT,1981) using the following relationship:

$$HHV\ (kJ/kg) = 2.326\ [\ 146.58C + 568.78\ H - 29.45 - 6.58A - 51.53\ (O+N)]$$

where,

C	= Carbon	% weight
H	= Hydrogen	% weight
A	= Ash	% weight
O	= Oxygen	% weight
N	= Nitrogen	% weight

The results are tabulated in Table 6.9.

5.4.4 Other determinations

5.4.4.1 Temperature measurements and thermocouple locations

The temperature of the air was measured by a mercury thermometer while the temperature in the system was measured by means of thermocouples. The thermocouple used was type K Cr/Al series manufacture by Shinko Ltd. All the thermocouples were calibrated by the supplier when they were purchased. The model used was SM-200 with a measuring range of between -50 to1200°C. The locations of the thermocouples are as shown in Figure 5.7 and 5.8 and are:

T_0 = Ambient temperature.

T_1 = Temperature at oxidation at the same level of the air nozzles and located at 42.5 cm from the outer wall of the gasifier.

T_2 = Temperature at reduction zone located at 15 cm above the lower grate and 42.5 cm from the outer wall.

T_3 = Temperature of product gas leaving the reactor. The exact location is 10 cm from the reactor wall.

T_4 = Temperature of gas 10 cm from the wall of the box filter.

T_5 = Temperature of product gas leaving the box filter 10 cm from the top of box filter.

T_6 = Temperature of product gas after condenser, located 10 cm from the wall of the condenser.

T_7 = Temperature at the air-product gas mixer

T_8 = Temperature at the engine exhaust fumes located at the engine exhaust pipe.

All the thermocouples except T_1 were stainless steel sheathed thermocouples. Thermocouple T_1 was specially modified to have a ceramic sheath at the end of the thermocouple in order to enable it to withstand the high temperature at the oxidation zone.

5.4.4.2 Pressure drop measurement

The pressure drop over the whole system was measured from run 22-73 while the pressure drop over the gasifier, the box filter and the cooler was measured after run 73.

The pressure drop was measured by means of differential water filled plastic U-tube manometer connected to short pipes welded on predetermined spots in the piping system (see Figure 5.8). The following pressure readings were recorded:

P_{gas} = Pressure drop across gasifier (Denoted by P_g in Figure 5.8)
P_{fil} = Pressure drop across box filter (Denoted by P_f)
P_{cool} = Pressure drop across air-cooled condenser (Denoted by P_c)
P_{sys} = Pressure drop across system (Not denoted in Figure 5.8)

5.4.4.3 Chemical composition of the gas

The composition of the product gas from the gasifier is an important parameter to be recorded for the preparation of the mass and energy balances and for calculating the heating value of the gas. The chemical composition of the product gas was measured by means of a portable Orsat gas analyser, Model Orsat-Lunge at the site of the research. The gas samples was drawn from the sampling point shown in Figure 5.7 and 5.8. Before the gas analysis was done, grease was applied at each of the valve to prevent leakage of gases. The burette jacket and the leveling bottle was then filled with water while the pipette was filled with the solvents shown in Table 5.3.

Table 5.3
Gas composition determination

Type of gas	Solvent	Specifications
CO	Cuprous oxide	100g Cu_2Cl_2 dissolved in solution in concentrated HCl and 0.2 g $SnCl_2$
CO_2	Potassium hydroxide solution	30g of KOH dissolved in 100 ml water.
O_2	Alkaline pyrogallol solution	6g $C_6H_3(OH)_3$ and 30g KOH dissolved in 100 ml water.
Hydrocarbons	Saturated bromine	5 % absorbed bromine water

The product gas was collected at the sampling point by the use of the rubber bulb in the apparatus. The gas was then bubbled through the respective reagents by opening the respective pipette and by the use of the levelling bottle. The volume of gas absorbed by the respective gases was determined by taking readings at the scale of the burette. Each gas analysis takes about 30-45 minutes to be performed and completed.

For the determination of H_2 and CH_4, the combustion method was used (Anon, 1985b; Kjellstrom and Stassen, 1983). This was done after the final reading of all the gases were absorbed by the respective solvents. A palladium duct was then heated up by an alcohol lamp until it was red hot for combustion of hydrogen to take place. The volume of hydrogen was determined by the change in the volume of water in burette. The same procedure was followed for the determination of the composition of hydrocarbons.

5.4.4.4 Tar, condensate, char and ash determination

During the gasification process, a substantial amount of tar, condensate, char and ash are produced. Each of these components were collected in the various parts of the gasifier. The weights of the each of components are needed for mass and energy balances analysis. However, the separation of the mixture into individual components is a very difficult task and some simplification of the process has to be assumed. It was found that most of the char and ash were deposited in the ash port and reduction zone of the reactor and in the cyclone (or drum cooler until run 73) dust chamber. Small amounts of char and ash were found in the box filter and the air-cooled condenser but this amount was ignored in the analysis because of the difficulty in separating them, especially from the tar deposits. On the other hand, tar and condensate were mainly condensed together at the conical base of the box filter and the air-cooled condenser. Some condensate was also reabsorbed by the char in the reactor during the cooling stage of the gasifier.

The amount of condensate reabsorbed by the char and ash could be easily determined by drying the char and ash collected. Tars are found mainly deposited on the charcoal and wood filters in the filter box, and with the

condensate in the box filter and gas condenser. Layers of tar are also found condensed on the connecting pipes and the walls of the filter box. These tar deposits on the pipes have to be ignored in the analysis because of difficulty in collecting them by scraping the walls of pipes and filter box.

a) Char and ash determination in ash port

For the determination of the char and ash content, the ash port was carefully opened and the mixture of wet char and ash were carefully removed by rotating the scraping grate with the help of the vertical axial shaft . The wet char and ash collected were all placed in polyurethane bags and sealed. Occasionally some wood chips were collected with the wet char and ash. These contaminants can however be removed physically and can easily be spotted due to the different size and colour of the chips. When all the wet char and ash in the reduction zone and ash port were removed, the lower plate of the gasifier was opened and any additional char and ash was further collected.

The wet char and ash sample was then dried in a ventilated oven at 103°C until a constant weight is obtained. The loss in weight is the condensate content. After drying, the ash was found to be in a very fine powdery form while the char was much more coarser. The dry mixture of char and ash was then passed through 3 layers of 0.2mm mesh size vibrating copper mesh to separate the char from the ash. The weights of the condensate, char and ash are recorded as follows:

Weight of condensate	= W1
Weight of char	= C1
Weight of ash	= A1

The same process was repeated with the wet char and ash collected at the cyclone dust chamber or the drum cooler.

The weights of condensate, char and ash are recorded as:

Weight of condensate	= W2
Weight of char	= C2
Weight of ash	= A2

b) Tar and condensate in filter box and air-cooled condenser

Tar and condensate were collected by draining them from the box filter and air-cooled condenser. The total weight of the mixture was recorded. The mixture of tar and condensate was then placed into a water bath rotary evaporator with a temperature of 103 °C to evaporate away the water and volatile organics in the mixture. The evaporation was a very slow process and generally took 2 days before a constant weight of tar was obtained. The loss in weight in the mixture is taken as the condensate content (since the condensate contains 99.2 % by weight of water-Table 6.17). The remaining weight in the evaporator is the tar content. The weights of condensate and tar are recorded as follows:

Weight of condensate	= W3
Weight of tar	= Z1

c) Tar and condensate trapped in wood and charcoal filter

Tar and condensate trapped in the filter medium was determined by drying the charcoal and wood chips at 103°C until a constant weight was obtained. The loss in weight was taken as the amount of condensate trapped with the filter medium. The gain in weight of the wood and charcoal over the original weight of wood and charcoal recorded before the run is the tar content. The weights of tar and condensate were recorded as follows:

Weight of condensate	= W4
Weight of tar	= Z2

d) Total weight of char, ash, condensate and tar collected

The total weight of char, ash, condensate and tar collected for the run was recorded as follows:

Total weight of char	=	C1+C2
Total weight of ash	=	A1+A2
Total weight of condensate	=	W1+W2+W3+W4
Total weight of tar	=	Z1+Z2

5.4.4.5 Average wood flow rate

Before the start of the gasifier, a predetermined weight of wood was added into the reactor to a predetermined level on the top of the fuel bunker. During the operation of the gasifier all wood added to the reactor was weighed and recorded. Before the gasifier was shut and sealed at the end of a run, the reactor was filled up with wood until the original level was reached. The amount of wood added during the run is the fuel consumption for that particular run. The average wood feed rate is calculated by dividing the total wood added by the total operation time of the gasifier.

5.4.4.6 Average diesel consumption rate

When the engine was operated on dual fuel mode, the diesel consumption was measured by topping up the diesel fuel tank to a predetermined mark. At the end of the run, diesel was added to the fuel tank until the predetermined level was reached. The volume of diesel consumed was taken as the volume of diesel added. The rate of diesel consumption is calculated by dividing the volume of diesel consumed with the total operation time.

5.4.4.7 Average gas flow rate

The gas flow rate was measured by means of a gas flowmeter loaned from the National University. The flowmeter is a Cole-Palmer Thermal gas flowmeter Model 3270. The flowmeter is positioned after the gas condenser. The flowmeter was carefully calibrated by the orifice meter at the National University of Malaysia before it was installed in the system. The gas flowmeter was able to read up to 300 m^3/h.

5.4.4.8 Dust and tar content of product gas

The tar and dust content of the product gas was sampled at the gas sampling point by the Department of Environment of Malaysia for dust and tar analysis. This additional data is used in the mass and energy balance analysis. Permission from the Department of Environment was only granted at the later stage of the research. The data is only available after run 73.

5.4.4.9 Average Power output

The electric power output of the engine was measured with a standard electrical wattmeter, voltmeter and ammeter.

5.4.4.10 Engine exhaust gas analyser

The engine exhaust gas composition was measured in run 83 with a newly acquired Bosch Exhaust Gas Analyser Model ET 008.00.

5.4.4.11 CO detector in the environment

Due to the poisonous nature of CO, the composition was constantly monitored by the Riken Keiki combined gas detector Model GX 999B.

5.5 BED ANALYSIS

A carbon conversion bed analysis profile was investigated in run 85. After the gasifier was sufficiently cooled, the upper lid of the gasifier was opened. About 500 g of wood/char samples at every 5 cm interval were carefully raked out from the gasifier bed for analysis. Wood/char samples were taken until the base of the wok throat was reached. The fixed carbon of each of the wood samples was analysed by the procedure described in British Standard BS 1016 (BSI, 1973). The results of the analysis are illustrated in Figure 5.9 where the distance of the samples taken were readjusted by taking the base of the throat as the origin.

From the bed analysis, it can be concluded that carbon conversion only takes place within the first 20cm from the base of the throat for the dry wood capacity used. Above this zone, very little carbon conversion takes place. The reason for the limited carbon conversion is not clear and no information of similar analysis could be found in the literature to be used for comparison.

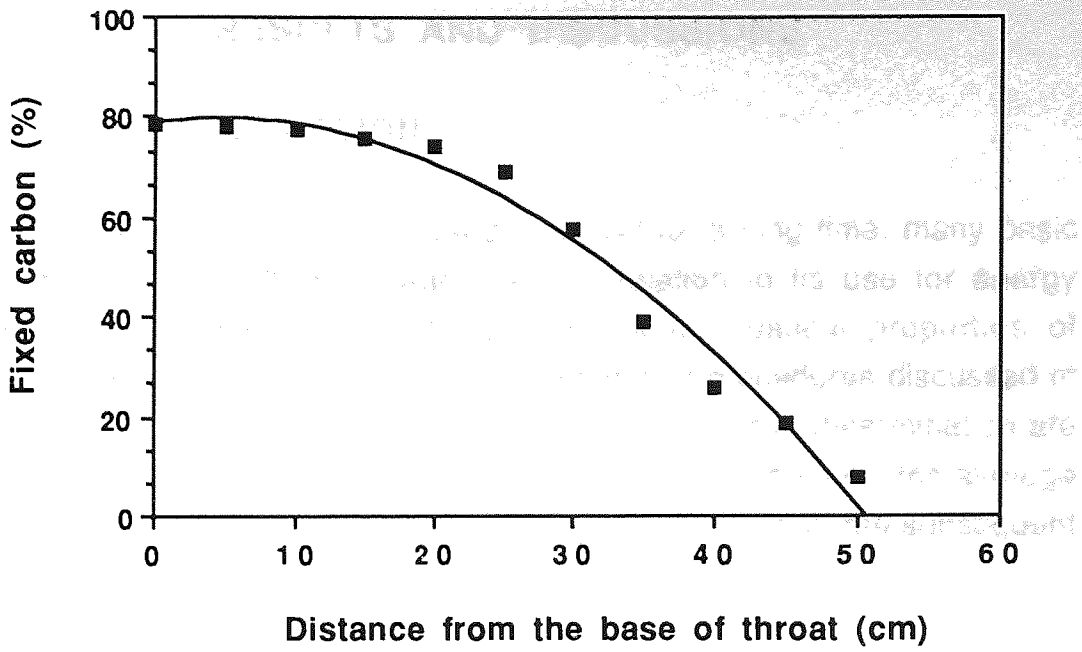


Figure 5.9 A carbon conversion bed analysis profile for run 85

CHAPTER 6

RESULTS AND DISCUSSIONS

6.1 INTRODUCTION

Although rubberwood has been used as a fuel for a long time, many basic properties have not been characterised in relation to its use for energy production. In this chapter the physical and chemical properties of rubberwood determined by using the experimental procedures discussed in Chapter 5 are presented. The results of the experimental determination are summarised in Appendix II. For the purpose of discussion, only the average value derived from the data in Appendix II is summarised in the subsequent sections.

6.2 PHYSICAL PROPERTIES

The major physical properties of rubberwood that are likely to affect the performance of a gasifier are the moisture content (wet basis), absolute density and the bulk density. The results of the experimental data are summarised in Table 6.1.using the experimental procedures discussed in Chapter 5 (section 5.4.2.1 and 5.4.2.2).

Table 6.1
Physical characteristics of rubberwood

Wood size cmxcmxcm	Moisture content (%)	Absolute density (kg/m^3)	Bulk density (kg/m^3)
3 x 3 x 1	8.2 (0.3)	677.3 (19.7)	304.0 (5.8)
3 x 3 x 2	8.1 (0.2)	671.3 (19.0)	296.0 (5.5)
3 x 3 x 3	7.9 (0.1)	669.5 (22.4)	294.0 (4.0)
3 x 3 x 4	7.8 (0.4)	674.8 (17.9)	285.3 (1.8)
3 x 3 x 5	7.6 (0.5)	671.8 (18.5)	279.8 (0.4)
3 x 3 x 6	7.5 (0.3)	673.8 (17.0)	275.3 (0.8)
Average	7.9	673.1	289.1

Note: Value in brackets are standard deviations of result.

From Table 6.1, rubberwood chips with an average moisture content of 7.9 % were found to have an absolute density of 673.1 kg/m^3 and an average

bulk density of 289.1 kg/m^3. On the basis of the average absolute density and bulk density, rubberwood has been classified as a medium density hardwood in literature published by the Malaysian Timber Industry Board (Anon, 1990).

6.3 CHEMICAL PROPERTIES

6.3.1 Chemical composition

The chemical composition, proximate and ultimate analysis of rubberwood were determined with the assistance of the Rubber Research Institute Malaysia using the method suggested by Browning (1967). The results of the analysis are summarised in Table 6.2.

Table 6.2
Chemical composition of rubberwood

Wood size cmxcmxcm	Cellulose %	Lignin %	Pentosan %	Water soluble %	Others %
3 x 3 x 1	44.7 (1.5)	23.1 (0.9)	16.9 (0.7)	6.6 (0.7)	8.8 (0.8)
3 x 3 x 2	45.2 (0.9)	22.8 (0.9)	17.2 (0.8)	5.9 (0.6)	8.9 (0.9)
3 x 3 x 3	45.0 (0.3)	22.4 (0.7)	17.3 (0.3)	6.2 (0.8)	9.3 (0.3)
3 x 3 x 4	45.1 (0.5)	22.9 (0.2)	16.7 (0.9)	6.2 (0.4)	9.2 (0.7)
3 x 3 x 5	45.1 (0.6)	22.1 (0.8)	16.5 (0.5)	4.5 (2.6)	11.9 (2.9)
3 x 3 x 6	45.1 (0.5)	22.4 (1.2)	16.7 (0.7)	6.5 (0.8)	9.3 (0.5)
Average	45.0	22.6	16.9	6.0	9.6

Note: Values in brackets are standard deviations of results.

Peel (1956) reported on the average composition of rubberwood as summarised in Table 6.3.

Table 6.3
Chemical composition of rubberwood (Peel, 1956)

Component	% composition by weight
Cellulose	43.9
Pentosans	18.0
Water solubles	8.8
Lignin and others	29.3
Total	100.0

The differences between the results reported by Peel (1956) and the experimental rubberwood may be due to different cultivation conditions. However the chemical properties of rubberwood are similar to those of other hardwoods published by Grabowski and Bain (1981).

6.3.2 Proximate and ultimate analysis

The proximate and ultimate analysis on a dry basis, determined by the Rubber Research Institute Malaysia, are summarised in Table 6.4 and Table 6.5 respectively.

Table 6.4
Proximate analysis of rubberwood on dry basis

Wood size cmxcmxcm	Volatile matter (%)	Ash (%)	Fixed carbon (%)
3 x 3 x 1	78.8 (1.2)	1.3 (0.2)	20.0 (1.0)
3 x 3 x 2	80.3 (1.0)	1.3 (0.2)	18.5 (0.9)
3 x 3 x 3	80.3 (1.6)	1.4 (0.1)	18.3 (1.6)
3 x 3 x 4	80.3 (1.1)	1.3 (0.2)	18.4 (1.0)
3 x 3 x 5	80.5 (0.7)	1.3 (0.1)	18.2 (0.8)
3 x 3 x 6	80.7 (0.5)	1.4 (0.1)	18.0(0.5)
Average	80.2	1.3	18.6

Table 6.5
Ultimate analysis of rubberwood, % dry basis

Wood size	Elemental components					
cmxcmxcm	C	H	O	N	S	Ash
3 x 3 x 1	48.2(0.4)	5.5(0.2)	44.9(0.5)	0.1(0.04)	0.1(0.04)	1.3(0.2)
3 x 3 x 2	48.5(0.3)	5.6(0.2)	44.5(0.2)	0.1(0.04)	0.2(0.05)	1.2(0.1)
3 x 3 x 3	48.0(0.4)	5.3(0.2)	44.6(0.7)	0.1(0.01)	0.1(0.04)	1.8(0.3)
3 x 3 x 4	47.8(0.5)	5.5(0.5)	44.9(0.8)	0.1(0.01)	0.1(0.01)	1.6(0.2)
3 x 3 x 5	48.9(0.7)	5.4(0.2)	43.9(0.5)	0.1(0.01)	0.1(0.01)	1.6(0.2)
3 x 3 x 6	48.9(0.5)	5.6(0.2)	43.6(0.4)	0.1(0.01)	0.1(0.01)	1.8(0.2)
Average	48.5	5.5	44.4	0.1	0.1	1.5

Tan and Scott (1989) reported the properties of 25 years old rubberwood is summarised in Table 6.6.

Table 6.6
Ultimate analysis of rubberwood (Tan and Scott, 1989)

Element	% weight composition	Normalised (daf)*
C	49.0	49.5
H	5.9	6.0
O	44.0	44.5
Ash	1.1	
Total	100.0	100.0

* daf = dry ash free

Table 6.7
Ultimate analysis of rubberwood determined experimentally by Rubber Research Institute Malaysia

Element	% weight composition*	Normalised (daf)
C	48.5	49.2
H	5.5	5.6
O	44.5	45.2
Ash	1.5	
Total	100.0	100.0

* Assuming N and S free

From Tables 6.6 and 6.7, the ultimate analysis of rubberwood determined experimentally is similar to that reported by Tan and Scott (1989). Due to the close agreement between the two methods of determining the ultimate analysis of rubberwood, the experimental values of the ultimate analysis can be used in mass and energy balance calculations.

6.3.3 Higher heating value

The higher heating value on a dry ash basis determined by the method discussed in Section 5.4.3.2 of Chapter 5 is summarised in Table 6.8.

There are three common methods of estimating the higher heating values of solid wood based on the ultimate analysis of wood. They are the Dulong-Bertholot method (Spiers, 1962), the Tillman method (Reed, 1988) and the IGT (IGT, 1978).

Table 6.8
Measured higher heating value of rubberwood

Wood size (cmxcmxcm)	kJ/kg (daf basis)
3 x 3 x 1	18256.8 (226.8)
3 x 3 x 2	18777.6 (443.6)
3 x 3 x 3	18579.5 (189.6)
3 x 3 x 4	18382.1 (321.6)
3 x 3 x 5	18278.0 (244.3)
3 x 3 x 6	18345.2 (309.4)
Average	18436.5

Of the three methods, the IGT equation has been reported by Graboski (Graboski,1981) as the most accurate equation developed to estimate the heating value of biomass with an average absolute error of 1.7 %. For the purpose of determining the accuracy of the above experimental values, the IGT method is used in calculating the higher heating value of wood with the relationship shown as follows:

$$HHV = 341C + 1323H + 68S - 15.3A - 120(O + N) \quad [6.1]$$

where,

HHV = higher heating value in kJ/kg
C = % carbon by weight
H = % hydrogen by weight
S = % sulphur by weight
A = % ash by weight
O = % oxygen by weight
N = % nitrogen by weight

Using equation 6.1 and the ultimate analysis data in Table 6.5, the calculated HHV of rubberwood is summarised in Table 6.9. From Table 6.9, the average HHV value determined by the IGT equation is 18385.3 kJ/kg. Graboski and Bain, (1981) reported that the average absolute error from IGT determination is 1.7 %. From Table 6.9, the average percentage difference between the IGT calculations and the measured value is 1.5 %. The average experimental HHV value is within the HHV value predicted by the IGT equation. Hence the experimental HHV can be used in all the energy balance calculations.

Table 6.9
Comparison between higher heating value of rubberwood by IGT equation and measured value, dry basis

Wood size cmxcmxcm	Calculated value kJ/kg	Measured value kJ/kg	% difference with IGT
3 x 3 x 1	18215.9 (449.5)	18256.8 (226.8)	0.2
3 x 3 x 2	18635.5 (238.0)	18777.6 (443.6)	0.8
3 x 3 x 3	18002.0 (388.2)	18579.5 (189.6)	3.2
3 x 3 x 4	18170.2 (814.9)	18382.1 (321.6)	1.2
3 x 3 x 5	18546.0 (228.5)	18278.0 (244.3)	1.4
3 x 3 x 6	18742.1 (274.2)	18345.2 (309.4)	2.1
Average	18385.3	18436.5	1.5

6.4 EXPERIMENTAL RUNS

During the research, a total of 101 runs were carried out. Details of the runs are summarised in Table 6.10. Because of difficulty in getting the wok throat in time during the early stages of the research (see section 5.1), the first 10 runs (R1-R10) were carried out without a throat in an open core configuration (Figure 5.1) to enable the author to familiarise himself with the proper operation of the gasifier. During these 10 runs two wood sizes were used, namely 3 cm x 3 cm x 1 cm and 3 cm x 3 cm x 6 cm. Only the wet feedrate and the gas composition were recorded. One run (R11) was conducted after the throat was installed (Figure 5.2). Because of delays in the procurement of thermocouples and the diesel engine, the data collected from Runs 12-22 were only the wet feedrate and the gas composition with wood sizes 3 cm x 3 cm x 1 cm and 3 cm x 3 cm x 6 cm. All runs from R1-R21 were considered as commissioning runs.

All the necessary instruments needed for the research were installed after run 21. The next 74 runs (R22-R95) were carried out to investigate the influence of wood capacity, particle size and moisture content on the performance of the gasifier in terms of the heating value of the gas and the cold gas efficiency. The last 6 runs (R96-R101) were designed to investigate the turndown characteristics and the performance of the gasifier on reducing the throat diameter by half. The operating conditions and objectives for all the experimental runs are summarised in Table 6.10.

Table 6.10
Summary of experimental runs and parameters investigated

Runs	Wood size	Parameters investigated
1-5	3 x 3 x 1	Commissioning runs without throat
6-10	3 x 3 x 6	Commissioning runs without throat
11	-	Commissioning run with throat installed
12-16	3 x 3 x 1	Commissioning runs and influence of moisture on performance of gasifier with throat
17-21	3 x 3 x 6	Commissioning runs and influence of moisture on performance of gasifier with a throat
22-29	3 x 3 x 1	Different capacities at constant moisture content of between 8-11 %
30-38	3 x 3 x 2	Different capacities at constant moisture content of between 8-11 %
39-47	3 x 3 x 3	Different capacities at constant moisture content of between 8-11 %
48-56	3 x 3 x 4	Different capacities at constant moisture content of between 8-11 %
57-64	3 x 3 x 5	Different capacities at constant moisture content of between 8-11 %
65-73	3 x 3 x 6	Different capacities at constant moisture content of between 8-11 %
74-79	3 x 3 x 1	Effect of 6 nozzles on different capacities at constant moisture of between 15-18 %
80-85	3 x 3 x 1	Effect of 3 nozzles on different capacities at constant moisture of between 15-18 %
86-90	3 x 3 x 1	Effect of moisture variation at constant wood consumption rate of 37-43 kg/h capacity
91-95	3 x 3 x 3	Effect of moisture variation at constant wood consumption rate of 37-43 kg/h capacity
96-101	3 x 3 x 1	Effect of throat diameter reduced from 20 cm to 10 cm at constant moisture content of between 15-18 %

6.5 PARAMETERS MEASURED

All the raw data for the above mentioned runs are given in Appendix III. A list of the parameters and range measured, as reported in Appendix III, is summarised in Table 6.11.

Table 6.11
Summary of parameters measured

Parameters	Unit	Range
Wood chip size	cm x cm x cm	1-6
Moisture content (wet basis)	%	8.0-54.0
Wood consumption rate (wet wood)	kg/h	4.5-85.0
Gas composition (CO_2,H_2,CH_4,CO)	% volume	0.5-30.0
Gas flow rate	Nm^3/h	20-175
Power output (Electrical)	kWe	4.5-33.5
Volume of diesel used	l/h	0.5-4.0
Tar collected	kg/h	0.3-6.0
Char collected	kg/h	0.8-5.0
Ash collected	kg/h	0.07-0.70
Condensate collected	kg/h	0.9-9.0
Tar content of product gas*	g/Nm^3	0.95-1.67
Dust content of product gas*	g/Nm^3	0.02-0.08
T_0-T_8 (temperature measurements-section 5.4.2)	°C	31-1005
P (pressure measurements-section 5.4.3)	mm of water	95-197

* Measured by Department of Environment of Malaysia.

6.6 MASS BALANCE FOR RUN 25

6.6.1 Components

The mass balance is one of the ways in which the the reliability of the data collected is tested. In theory, the total mass input must be equal to the total mass output. Experimental errors or omissions in measurements will invariably lead to discrepancies in the mass balance. The usual method to quantify the discrepancies is the closure of the mass balance which is defined as the percentage ratio of the total output mass to that of the total input mass. For the mass balance determination, a sample calculation for run 25 is given below and the spreadsheet results in Appendix IV are based on this method of computation. The mass balance flow diagram is illustrated in Figure 6.1.

a) Total mass inputs into the gasifier system

1. Wood (dry ash free basis), H_20 and ash.
2. Air consisting of O_2 and N_2 and H_20

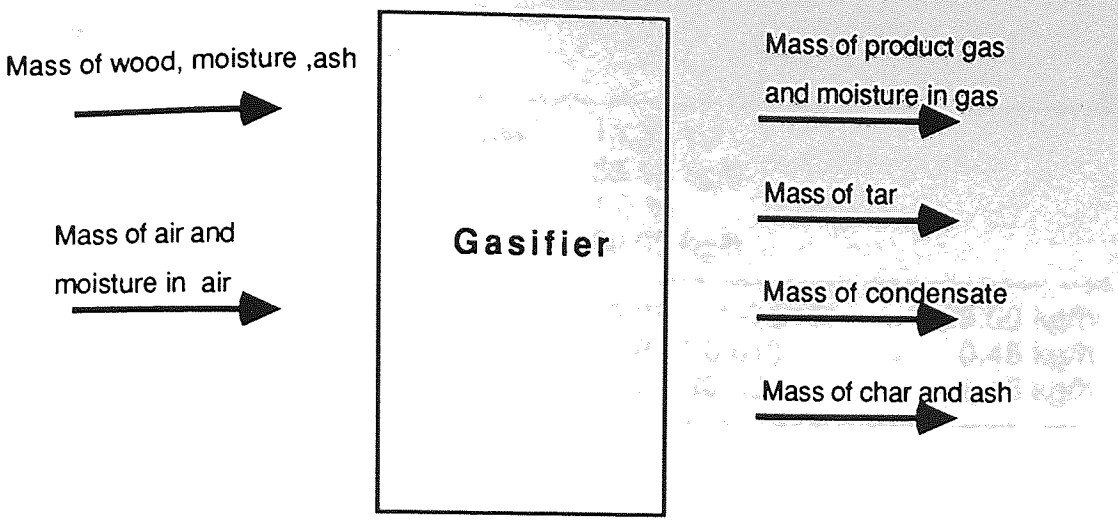


Figure 6.1 Mass balance flow diagram

b) Total mass output from gasifier system

1. Product gas consisting of N_2, CO_2, CO, CH_4, H_2, O_2, moisture in gas
2. Tar*
3. Condensate*
4. Char*
5. Ash*

*As determined by the method discussed in Chapter 5.

Mass balance closure

$$\text{Mass balance closure} = \frac{\text{Total mass output}}{\text{Total mass input}} * 100 \qquad [6.2]$$

Similarly an elemental balance closure in terms of elemental components of C, H, O and N and a water balance can also be determined by using equation [6.2] above.

6.6.2 Wood input

The molecular formula of rubberwood derived from data obtained from Table 6.7 is $C_6H_8O_4$ giving a molecular weight of 144 kg/kg mole (daf) on a C_6 basis. From the raw data in Appendix III, the data for the mass inputs from wood is summarised in Table 6.12.

Table 6.12
Mass inputs from wood

Moisture content of wood (wet basis)	10.30 %		
Mass flow of wet wood	33.50 kg/h		
Ash content of wood	1.5 %		
Dry wood and ash mass flow	30.05 kg/h		
Dry ash free wood flow	30.05 * (1-0.015)	=	29.60 kg/h
Dry ash flow	30.05 * 0.015	=	0.45 kg/h
Mass flow of water in wood	33.50-30.05	=	3.45 kg/h

6.6.3 Air intake

From Perry (1984), air contains 23.52 % by weight of oxygen and 76.48 % by weight of nitrogen. Hence, 0.2352A kg of oxygen and 0.7648A kg of nitrogen entered the gasifier per hour where A is the mass flow of the air.

$$\text{Dry molecular weight of air} = \sum MW_i * x_i \qquad [6.3]$$

where,
MW_i = Molecular weight of the component i in air
x_i = Molar fraction of component i in air

Using equation 6.3,

Dry molecular weight of air = 1/(0.2352/32 + 0.7648/28)
= 28.94 kg/kg mole

The relative humidity and temperature, averaged over the operating time of the gasifier and measured by the Vaisaila humidity meter Model HMI 31 and temperature probe T_0 were 92 % and 32.7°C respectively. From the air-water vapour diagram (Perry, 1984), the air contained 0.0276 kg water/kg dry air. Thus the moisture content of air in this case is:

$$\frac{0.0276}{1 + 0.0276} * 100 = 2.69\ \%$$

Thus the air contained 2.69 %, 74.42 % and 22.89 % by weight of moisture, nitrogen and oxygen respectively.

Molecular weight of wet air = 0.0269 * 18 + 0.7442 * 28 + 0.2289 * 32
= 28.64 kg/kg mole

6.6.4 Product gas

The volumetric flow rate of the clean wet gas leaving the gasification system measured by the gasmeter illustrated in Figure 5.7 and 5.8 is given by:

Volumetric gas flow rate = 89.3 Nm^3/h

The average pressure drop across the gasifier system is:

P_{sys} = 3.9 mm Hg.

Hence, pressure across the gasifier system is:

(760.0 - 3.9) mm Hg = 756.1 mm Hg.

The average temperature at gasifier system outlet measured by thermocouple, T_7 = 317.3 K and the dry gas analysis of the sampled gas from Appendix III is given in Table 6.13.

Table 6.13
Dry gas analysis

Components	% by volume
H_2	18.4
CO_2	12.3
CO	18.9
CH_4	0.6
N_2	49.8
Total	100.0

Using equation 6.3, the molecular weight of the dry gas stream is as follows:

= 0.184 * 2 + 0.123 * 44 + 0.189 * 28 + 0.006 * 16 + 0.498 * 28

= 25.11 kg/kg mole.

The product gas is in direct contact with condensed water and hence can be assumed to be saturated with water at the outlet conditions. The molar ratio of water in the gas X_w can be determined by:

$$X_w = \frac{P_w}{P-P_w} \qquad [6.4]$$

where P_w = vapour pressure of water at 317.3 K

P = pressure of product gas at the outlet
= 756.1 mm Hg

From Perry (1984), P_w = 69.33 mm Hg

From equation 6.1, $X_w = \frac{69.33}{756.1-69.33}$

= 0.101 kg mole water/kg mole dry gas.

The composition of the wet gas is summarised in Table 6.14.

Table 6.14
Percentage composition of wet gas

Gases	% composition
H_2	16.5
CO_2	11.1
CO	17.0
CH_4	0.5
N_2	44.8
H_2O	10.1
Total	100.0

Using equation 6.3,the molecular weight of the wet product gas is:
= 0.165 * 2 + 0.111 * 44 + 0.17 * 28 + 0.005 * 16 + 0.448 * 28 + 0.101 * 18
= 24.39 kg/kg mole

The gas mass flow rate F_{gas} at the outlet condition of 317.3 K and 756.1 mm Hg can be determined by assuming that the product gas is treated as an ideal gas.

$$F_{gas} = \frac{Q_{gas} * P * M_{gas}}{R * T} \qquad [6.5]$$

where,
Q_{gas} = volumetric gas flow rate at gasifier system outlet (see Appendix III)
P = pressure of product gas at gasifier system outlet
M_{gas} = molecular weight of wet product gas
T = temperature at gasifier system outlet
R = constant (0.08205 m^3 atm/kgmole K)

From equation 6.5, $F_{gas} = \frac{89.3 * 756.1 * 24.39}{760 * 0.08205 * 317.3}$

= 83.23 kg wet gas/h

Thus the dry gas mass flow is:

$$83.23 * (1\text{-}0.101) = 74.83 \text{ kg dry gas /h}$$

$$\text{Mass flow of water in gas} = 83.23 - 74.83 \text{ kg/h} = 8.40 \text{ kg/h}$$

The dry volumetric flow of gas can be calculated by assuming that the product gas is an ideal gas and the dry volumetric gas flow at STP is given as:

$$Q_{gas}\,(STP) = \frac{74.83 * 0.08205 * 273}{25.11} \text{ Nm}^3 \text{ dry gas/h}$$

$$= 66.75 \text{ Nm}^3\text{/h}$$

6.6.5 Air

The volumetric flow rate of air entering the gasifier system could not be measured accurately in the experiment because of reasons discussed in Chapter 5. The dry mass flow of air is, therefore, calculated from the nitrogen balance by assuming that the nitrogen in the product gas does not take part in the gasification process and that the mass of nitrogen in the product gas is equal to the mass of nitrogen in the air fed into the gasifier.

Thus,

$$F_{N2}\,(air) = F_{N2}(gas)$$

$$F_{N2}\,(air) = \frac{F_{air} * x_{N2}(air) * MW_{N2}}{MW_{air}} \qquad [6.6]$$

$$F_{N2}(gas) = \frac{F_{gas} * x_{N2}(gas) * MW_{N2}}{MW_{gas}} \qquad [6.7]$$

where,

F_{air} = mass flow of dry air

$x_{N2}(air)$ = volume fraction of N_2 in dry air

MW_{N2} = Molecular weight of N_2

MW_{air} = molecular weight of dry air

F_{gas} = mass flow of dry gas

$x_{N2}(gas)$ = volume fraction of N_2 in dry gas

MW_{gas} = molecular weight of dry gas

Equating equations 6.6 and 6.7,

$$F_{air} = \frac{F_{gas} * x_{N2}(gas) * MW_{air}}{x_{N2}(air) * MW_{gas}}$$

$$= \frac{74.83 * 0.498 * 28.94}{0.7442 * 25.11}$$

$$= 57.71 \text{ kg dry air/h}$$

Dry air volumetric flow rate at STP is Q_{air} (STP)

$$= \frac{57.71 * 0.08205 * 273}{28.94}$$

$$= 44.67 \text{ Nm}^3 \text{ dry air/h}$$

Using F_{air} and data from Section 6.6.2,

Mass flow of water in air = 57.71 * 0.0269 kg/h = 1.55 kg/h

6.6.6 Tar content

The mass flow rate of tar, (see section 5.4.4.4) F_{tar} = 0.98 kg/h.

The tar yield is about 3.3 % the weight of wood (daf). The tar yield is higher than most reported tar yields of 1 % (Chee, 1986; Walawender, 1985). The reason for the higher tar yield is due to the presence of latex in rubberwood which will be collected together with wood tar (Hoi and Puad, 1990).

The ultimate analysis of tar is summarised in Table 6.15.

Table 6.15
Ultimate analysis of tar (Harris, 1989)

Elements	%
C	74.8
H	8.6
O	16.6
Total	100.0

6.6.7 Char content

The mass flow rate of char (see section 5.4.4.4) is F_{char} = 1.07 kg/h

The elemental analysis of char is summarised in Table 6.16.

Table 6.16
Elemental analysis of char (Harris, 1989)

Elements	%
C	96.3
H	1.2
O	2.5
Total	100.0

6.6.8 Ash content

The mass flow rate of ash, (see Section 5.4.4.4) F_a = 0.35 kg/h

6.6.9 Water in condensate

Mass flow rate of condensate (see section 5.4.4.4) = 1.69 kg/h.
The analysis of the condensate is summarised in Table 6.17.

Table 6.17
Condensate analysis

Parameter	% by weight
pH	8.5
water content	99.2
insoluble matter and hydrocarbon	0.8
Total	100.0

Since the water content in the condensate is 99.2 % by weight, the mass flow rate of condensate, F_w = 1.69 * 0.992 kg/h = 1.68 kg/h

6.6.10 Summary of mass balance data

The relevant data derived from the earlier sections which will be used for the determination of the overall mass balance is summarised in Table 6.18.

Table 6.18

Summary of mass balance data for run 25

Wood		Comment
Moisture content of wood	10.3 % wet basis	measured
Dry ash free wood flow rate	29.60 kg/h	derived
Dry mass ash flow rate	0.45 kg/h	derived
Mass flow of water in wood	3.45 kg/h	derived
Air		
Air moisture content	2.69 % by weight	derived
Dry nitrogen content in air	74.42 %by weight	assumed
Dry oxygen content in air	22.89 % by weight	assumed
Molecular weight of dry air	28.94	derived
Molecular weight of wet air	28.64	derived
Dry air mass flow	57.71 kg/h	derived
Dry volumetric air flow at STP	44.67 Nm^3/h	derived
Mass flow of water in air	1.55 kg/h	derived
Product gas		
Molecular weight of dry gas	25.11	derived
Molecular weight of wet gas	24.39	derived
Wet volumetric flow rate	89.30 Nm^3/h	measured
Dry volumetric gas flow rate at STP	66.75 Nm^3/h	derived
Mass flow rate of wet gas	83.23 kg/h	derived
Mass flow rate of dry gas	74.83 kg/h	derived
Mass flow rate of water in gas	8.40 kg/h	derived
Other products		
Dry mass flow of tar	0.98 kg/h	measured
Dry mass flow of char	1.07 kg/h	measured
Dry mass flow of ash	0.35 kg/h	measured
Mass flow of water in condensate	1.68 kg/h	measured

6.7 OVERALL MASS BALANCE ANALYSIS

The overall mass balance analysis can be summarised and calculated as shown below.

6.7.1 Total mass input

From Table 6.18,

Dry mass flow of wood = 29.60 kg/h

Dry mass flow of ash = 0.45 kg/h

From Table 6.18 and section 6.6.3,

$$\text{Dry mass flow of oxygen} = \frac{57.71 * 0.2289 * 32}{28.94}$$

$$= 14.61 \text{ kg } O_2/h$$

Similarly,

$$\text{Dry mass flow of nitrogen} = \frac{57.71 * 0.7442 * 28}{28.94}$$

$$= 41.55 \text{ kg } N_2/h$$

From Table 6.18,

Mass flow of water in wood = 3.45 kg/h

Mass flow of water in air = 1.55 kg/h

Total mass input = 29.60+0.45+14.61+41.5+3.45+1.55 kg/h

= 91.21 kg/h

6.7.2 Total mass output

From Table 6.18,

Dry gas mass flow	= 74.83 kg/h
Mass flow of water in gas	= 8.40 kg/h
Tar output	= 0.98 kg/h
Char output	= 1.07 kg/h
Ash output	= 0.35 kg/h
Condensate	= 1.68 kg/h
Total mass output	= 87.32 kg/h

6.7.3 Mass balance closure

$$\text{Mass balance closure} = \frac{87.32}{91.21} * 100\ \% = 95.74\ \%$$

6.8 ELEMENTAL BALANCE

The elemental balance can be calculated in terms of the elements of each compound entering or leaving the gasifier. The elements considered are carbon C, hydrogen H, oxygen O and nitrogen N.

6.8.1 Elemental inputs

6.8.1.1 Total carbon input

Since only wood contains carbon, the dry carbon input mass flow, $F_{C(input)}$, is equal to the dry carbon mass flow rate in wood, $F_{C(wood)}$. Thus,

$$F_{C(input)} = F_{C(wood)} \quad [6.8]$$

$$F_{C(wood)} = F_{wood} * y_{c(wood)} \quad [6.9]$$

where,

F_{wood} = mass flow rate of dry wood

$y_{c(wood)}$ = % by weight of carbon in wood

Substituting equation.6 9 into 6.8,

$$F_{C(input)} = F_{wood} * y_{c(wood)} \quad [6.10]$$

Using equation 6.10 and data from Table 6.12 and Table 6.7,

$$F_{C(input)} = 29.60 * 0.492 = 14.56 \text{ kg/h of C}$$

6.8.1.2 Total oxygen input

The dry mass input flow of oxygen is the oxygen component in wood, water in wood, water in dry mass air input and water in air. Hence $F_{O2\ (input)}$ is:

$$F_{O2}(wood)+F_{O2}(water\ in\ wood)_{+}F_{O2}(air)_{+}F_{O2}(water\ in\ air) \quad [6.11]$$

Using equation 6.11 and data from Table 6.7, Table 6.12, Table 6.18 and data in section 6.6.2.

$$F_{O2\ (input)} = (29.60*0.452)+(3.45*16/18)+(0.2289*57.17)+(1.55*16/18)$$

$$= 31.03 \text{ kg/h}$$

6.8.1.3 Total hydrogen input

The dry hydrogen mass flow input, is the hydrogen component in wood, water in wood and water in air. Hence , $F_{H2(input)}$ is:

$$F_{H2}\ (wood)+F_{H2}(water\ in\ wood)+F_{H2}(water\ in\ air) \quad [6.12]$$

Using equation 6.12 and data from Table 6.7, Table 6.12 and Table 6.18,

$F_{H2(input)}$ = 29.60 * 0.056+3.45 * 2/18+1.55 * 2/18 = 2.21 kg H/h

6.8.1.4 Total nitrogen input

$F_{N2(input)}$ = 41.55 kg/h

6.8.2 Elemental output

Using data from Table 6.13 and Table 6.18,
The dry mass flow rate of the respective gases are as follows:

$$F_{H2} = \frac{74.83 * 0.184 * 2}{25.11} = 1.10 \text{ kg/h}$$

$$F_{CO} = \frac{74.83 * 0.189 * 28}{25.11} = 15.77 \text{ kg/h}$$

$$F_{CO2} = \frac{74.83 * 0.123 * 44}{25.11} = 16.13 \text{ kg/h}$$

$$F_{CH4} = \frac{74.83 * 0.006 * 16}{25.11} = 0.29 \text{ kg/h}$$

$$F_{N2} = \frac{74.83 * 0.498 * 28}{25.11} = 41.55 \text{ kg/h}$$

6.8.2.1 Total carbon output

The output components containing carbon are CO, CO_2, CH_4, tar and char.

The dry mass flow rate of carbon output is:

$$F_{C(output)} = F_C(CO)+F_C(CO_2)+F_C(CH_4)+F_C(tar)+F_C(char) \quad [6.13]$$

where,

$F_C(CO)$ = dry mass flow rate component of carbon in CO
$F_C(CO_2)$ = dry mass flow rate component of carbon in CO_2
$F_C(CH_4)$ = dry mass flow rate component of carbon in CH_4
$F_C(tar)$ = dry mass flow rate component of carbon in tar
$F_C(char)$ = dry mass flow rate component of carbon in char

Substituting the respective dry mass flow rate of the respective gas components above into equation 6.13 and using data from Table 6.15 and Table 6.16 and Table 6.18, $F_{C(output)}$ is:

= 15.77*12/28+16.13*12/44+0.29*12/16+0.98*0.748+1.07*0.963
= 13.13 kg/h

6.8.2.2 Total oxygen output

Using the same method as in the determination of the carbon output, the output components that contains oxygen are: CO, CO_2, water in gas, tar, condensate and char.

Hence, $F_{O(output)}$ is:

$$F_{O(CO)}+F_{O(CO_2)}+F_{O(\text{water in gas})}+F_{O(tars)}+F_{O(condensate)}+F_{O(char)} \quad [6.14]$$

Using equation 6.14 and data from Table 6.15, Table 6.16, Table 6.17 and Table 6.18, $F_{O(output)}$ is:

= (15.77*16/28) + (16.13 * 32/44) + (8.40 * 16/18) + (0.98 * 0.166)
+ (1.68 * 16/18) + (1.07 * .025)
= 29.89 kg/h

6.8.2.3 Total hydrogen output

The output components that contains hydrogen are: H_2, CH_4, tars, water in condensate, water in gas and char, $F_{H(output)}$ is:

$$F_{H2}+F_{H(CH4)}+F_{H(tars)}+F_{H(\text{condensate})}+F_{H(\text{water in gas})}+F_{H(char)} \quad [6.15]$$

Using equation 6.15 and data from Table 6.15, Table 6.16, Table 6.17, Table 6.18 and the above mass flow rate of the respective gases, $F_{H(output)}$ is:

=(1.10*1)+(0.29*4/16)+(0.98*0.086)+(1.68*2/18)+(8.40*2/18) +(1.07*.012)
= 2.39 kg H/h

6.8.2.4 Total nitrogen output

$$F_{N(output)} = 41.55 \text{ kg/h}$$

6.8.3 Elemental closure

6.8.3.1 Carbon closure

$$\text{Closure for carbon} = \frac{13.13}{14.56} * 100 = 90.19\ \%$$

6.8.3.2 Oxygen closure

$$\text{Closure for oxygen} = \frac{29.89}{31.03} * 100 = 96.32\ \%$$

6.8.3.3 Hydrogen closure

$$\text{Closure for hydrogen} = \frac{2.39}{2.21} * 100 = 107.94\ \%$$

6.8.3.4 Nitrogen closure

$$\text{Closure for nitrogen} = \frac{41.55}{41.55} * 100 = 100.00\ \%$$

The nitrogen balance yielded a closure of 100 % because it was based on the assumption that nitrogen does not take part in the gasification process and hence the total dry mass of nitrogen in the air fed into the gasifier is equal to the dry mass of nitrogen in the product gas.

6.9 WATER BALANCE

6.9.1 Total water input

Mass flow of water in wood = 3.45 kg/h
Mass flow of water in air = 1.55 kg/h
Total mass of water input = 5.00 kg/h

6.9.2 Total water output

Mass of water in gas = 8.40 kg/h
Mass of water in condensate = 1.68 kg/h
Total mass of water output = 10.08 kg/h

6.9.3 Water closure

$$\text{Closure for water} = \frac{10.08}{5.00} * 100$$

$$= 201.49\ \%$$

The high closure for the water balance suggested that additional water is produced during the gasification process. From the above the total mass of water produced and condensed during gasification was 2.01 times higher than the total mass of water entering into the gasifier as moisture in wood and air. Jenkins (1980) proposed the following relationship to describe the relationship between the moisture of the wood and product gas by the use of a choke plate throated gasifier. The relationship can be summarised as follows:

$$MC_{gas} = 3.6686 + 0.5922 * (MC_w) \qquad [6.16]$$

where,

MC_{gas}= moisture content of the product gas as volume percentage

MC_w = moisture content of wood expressed on a wet basis

According to equation 6.16, the moisture content of the product gas is expected to be 9.77 % by volume. The moisture content of the wet gas using experimental results is 10.1 % by volume (see Table 6.14). The close agreement between Jenkin's prediction and the author's experimental data confirmed further evidence that water is produced during the gasification process most probably by the water shift reaction:

$$CO_2 + H_2 = CO + H_2O$$

6.10 OTHER MASS BALANCE INDICATORS

There are a number of other related mass efficiency indicators which have been defined to compare the performance of gasifier under different operating conditions. The most widely used indicators are:

6.10.1 Air fuel ratio

Air fuel ratio is defined as:

$$\frac{\text{Mass of dry air input}}{\text{Total mass of dry ash free wood}} \qquad [6.17]$$

$$\text{or} \quad \frac{\text{Volume of dry air}}{\text{Total mass of dry ash free wood}} \qquad [6.18]$$

Using data from Table 6.18 and equation 6.17,

$$\text{Air fuel ratio} = \frac{57.71}{29.60}\ \text{kg/kg} = 1.95\ \text{kg/kg}$$

Using data from Table 6.18 and equation 6.18,

$$\text{Air fuel ratio} = \frac{44.67}{29.60}\ \text{Nm}^3\text{/kg} = 1.51\ \text{Nm}^3\text{/kg}$$

Groeneveld et al., (1980) obtained an air fuel ratio of 1.81 Nm^3/kg for gasifying wood chips at 18 % moisture content in a downdraft gasifier. Walawender et al., (1988) published experimental gasification data and reported that the air fuel ratio ranged from 0.99 to 2.08 Nm^3/kg for wood chips having a moisture content of 5.5 to 16.5 %. However, an explanation for the variation was not available.

In order to analyse the influence of dry wood capacity on air fuel ratio, runs 22-29 were chosen for analysis because of good mass balance closures for the runs. The average moisture content for the runs was 8.8-10.7 % wet basis and the wood size is 3 cm x 3 cm x 1 cm. The result of the analysis is given in Figure 6.2.

From Figure 6.2, the average air fuel ratio obtained experimentally varies from 0.84-2.11 Nm^3/kg for all the runs. The air fuel ratios obtained shows good agreement with the experimental data obtained by Walawender et al., (1988).

The air fuel ratio was also found to be dependent on the dry wood feedrate. The same correlation was also reported by Jenkins and Goss, (1980). The air fuel ratio has a vitally important effect on the gasifier performance because it regulates the fuel consumption rate. However Jenkins and Goss, (1980) reported that this ratio is not easily controlled and should not be arbitrarily assumed.

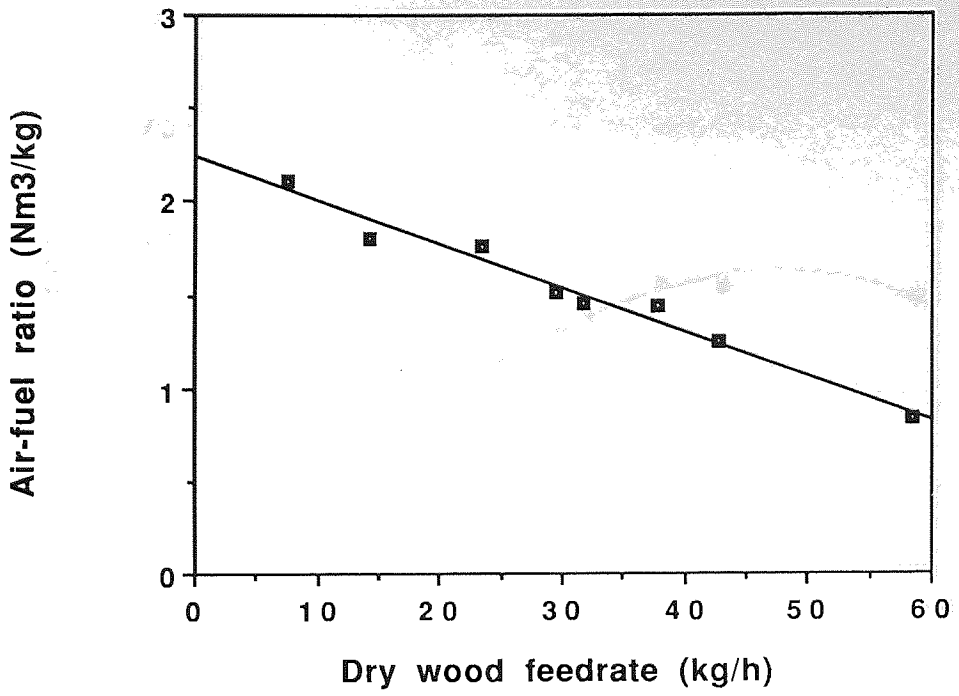


Figure 6.2 Influence of dry wood feedrate on air-fuel ratio for runs 22-29

6.10.2 Specific gasification rate

Specific gasification rate is defined as:

$$\frac{\text{Total dry volumetric gas flow}}{\text{Cross sectional area across throat}} \qquad [6.19]$$

Cross sectional throat area = $\pi * 0.10^2$ = 0.0314 m^2

Using data from Table 6.18 and equation 6.19,

$$\text{Specific gasification rate} = \frac{66.75}{0.0314} = 2125.69 \text{ Nm}^3/\text{m}^2\text{h}$$

In order to analyse the influence of dry wood capacity on the specific gasification rate, the same runs as in section 6.10.1 are analysed. The result of the analysis is summarised in Figure 6.3.

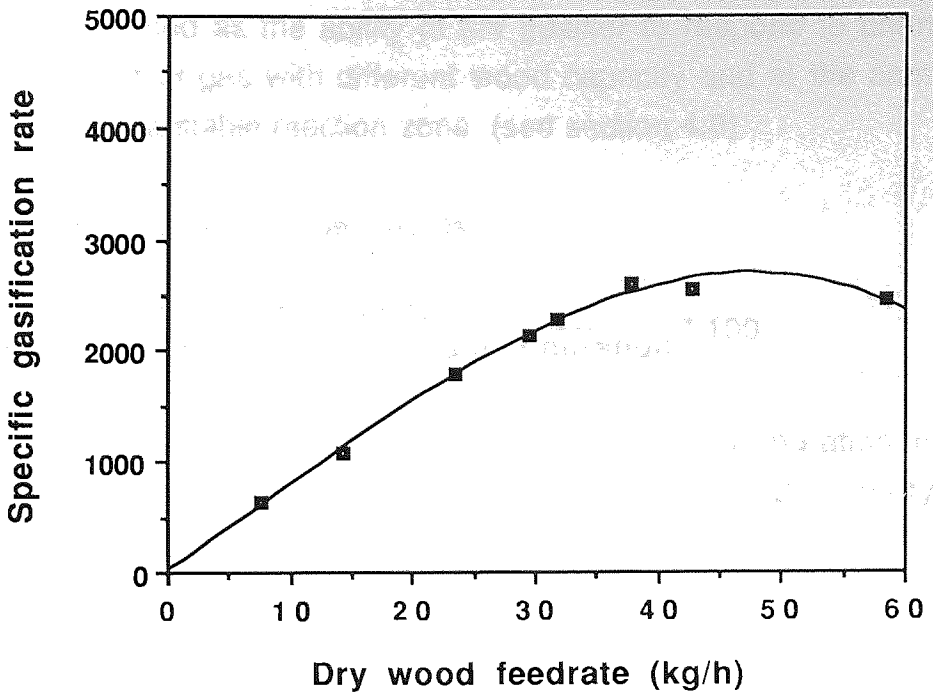


Figure 6.3 Influence of dry wood feedrate on specific gasification rate for runs 22-29

The specific gasification rate of the gasifier is an indicator of the size of the gas producer needed for a given throughput. This parameter is strongly dependant on the type of gas producer and on the fuel. The maximum permissible specific gasification rate for downdraft gasifiers is a well established number and is given as 10000 Nm^3/m^2h. The minimum permissible specific gasification rate will however be dependant on the shape of the throat, and how well the system is insulated as well as uniform air distribution. A minimum permissible specific gasification rate of 350 Nm^3/m^2h has been found suitable for the Imbert type gasifier (Jenkins 1980; Groeneveld et al., 1980). However, the comparison of the specific gasification rate in throated downdraft gasifier reported in most literature is dependant on which cross-sectional area that is used as reference. Because this is not always specified, there is a high uncertainty in reported values. From Figure 6.3, the minimum specific gasification rate for rubberwood with size 3 cm x 3 cm x 1 cm is about 626 Nm^3/m^2h while the maximum specific gasification rate is about 2530 Nm^3/m^2h.

6.10.3 Turndown ratio

Turndown is defined as the ability of the gasifier to respond to changes in demand for product gas with different wood capacity and at the same time be operated with a stable reaction zone (see section 4.9).

The turndown percentage is defined as:

$$\frac{\text{Dry wood capacity}}{\text{Maximum dry wood capacity for stable operation}} * 100$$

From runs 22-29, the maximum wood capacity for stable operation in terms of power output is 37.77 kg/h (see section 6.21.2). For run 25, the dry wood capacity is 29.60 kg/h. Hence, turndown percentage is:

$$= \frac{29.60}{37.77} * 100 \qquad = 78.36\ \%$$

$$\text{Turndown ratio} \quad = \frac{37.77}{29.60} \qquad = 1.28$$

The influence of dry wood capacity on turndown ratio is discussed in section 6.21.6.

6.10.4 Equivalence ratio

Equivalence ratio is defined as the ratio as:

$$\frac{\text{Actual oxidant/mass of dry ash free wood}}{\text{Stoichiometric oxidant/mass of dry ash free wood}} \qquad [6.20]$$

The complete combustion of rubberwood can be illustrated by:

$$C_6H_8O_4 + 6\ O_2 \quad = 6CO_2 + 4H_2O \qquad [6.21]$$

From equation 6.21,

Weight of 6.1 moles of oxygen = 6 * 32 = 192 kg/kg mole

Weight of 1.0 mole of rubberwood = 144 kg/kg mole

Hence,

$$\frac{\text{stoichiometric oxidant}}{\text{mass of dry ash free wood flow}} = \frac{192}{144} = 1.33$$

From Section 6.7.1, weight of O_2 input = 14.61 kg/h

From Table 6.18, weight of dry wood input = 29.60 kg/h

Hence,

$$\frac{\text{Actual oxidant}}{\text{mass of dry ash free wood used}} = \frac{14.61}{29.60} = 0.493$$

$$\text{From equation 6.21, Equivalence ratio} = \frac{0.493}{1.33} = 0.37$$

The influence of dry wood capacity on the equivalence ratio for runs 22-29 is summarised in Figure 6.4.

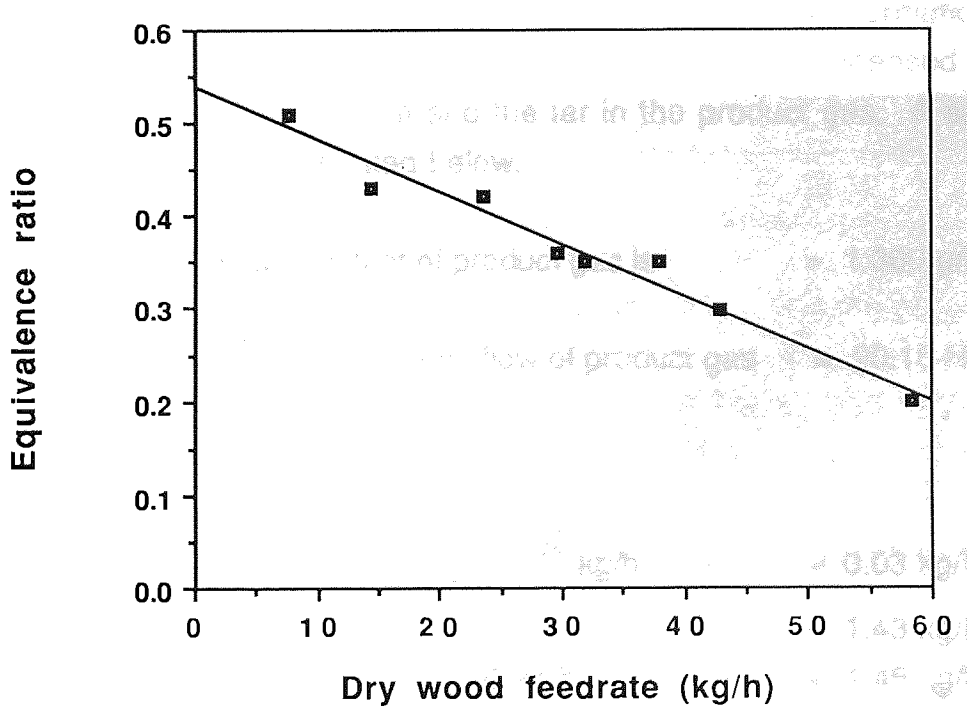


Figure 6.4 Influence of dry wood feedrate on equivalence ratio for runs 22-29

The relationship between the dry wood feedrate and equivalence ratio is similar to that of the air fuel ratio relationship. Reed and Jantsen., (1979)

reported that the equivalence ratio, for gasification process as they take place in practice lies between 0.2-0.4 for steady state operation. They also concluded that the chemical energy of the product gas reached a maximum when the equivalence ratio is 0.275. For the experimental runs, the equivalence ratio was found to be between 0.2-0.51.

6.11 SUMMARY OF MASS AND ELEMENTAL BALANCES DETERMINATION

6.11.1 Mass and elemental balances for runs 22-73

Using the same method of computation as in Section 6.6, the mass and elemental balances for runs 22 to runs 73 are summarised in Appendix IV.

6.11.2 Mass and elemental balances for runs 74-101

For runs 74-101, the tar content of the product gas was measured by the Department of Environment of Malaysia. With the additional information the total tar content of each individual run is the sum of the tar condensed in the gas cleaning and cooling system and the tar in the product gas. A sample calculation for run 74 is illustrated below.

From Appendix III, the tar content of product gas is = 1.360 g/Nm^3

From Appendix IV , the dry volumetric flow of product gas = 20.10 Nm^3/h

Hence total tar content in product gas is:

$$= \frac{20.10 * 1.360}{1000} \text{ kg/h} \quad = 0.03 \text{ kg/h}$$

From Appendix IV, total tar condensed = 1.43 kg/h

Hence total tar collected = 1.43 +0.03 kg/h = 1.46 kg/h

Using the additional information of the tar content in the product gas, the mass balances for runs 74-101 were computed using the same procedure as discussed earlier.

The mass and elemental balances of runs 22-101 are summarised in Appendix IV.

6.12 CONCLUSION OF MASS AND ELEMENTAL BALANCES

Mass balances have only occasionally been used to evaluate the performance of downdraft gasifiers because it is difficult and expensive to successfully measure all the operating parameters in a gasifier (Chee, 1988; Chern, 1987). Fairly complete mass balances data have been published on commercial downdraft gasifiers systems (Graham, 1981; Goss, 1982; Walawender, 1985; 1987; Graboski, 1987). The overall mass and elemental balances for runs 22-101 are summarised in Table 6.19 and shown in Figure 6.5.

Table 6.19
Mass and elemental balance closures

Closure range, %	Mass balance	C	O	H
>110	0	2	0	15
100-110	1	9	7	32
90-100	57	34	34	15
80-90	16	23	25	12
<80	3	9	11	3
Average	92.65	91.13	89.30	100.35

The average mass balance was found to be 92.65%. The majority of the mass balance closures lie in the range 80-100%. However, three runs (run 63, run 64 and run 90) gave mass balance closures of less than 80%. Engine trouble developed during runs 62, 63 and 64 resulted in erratic power output. In fact the engine broke down completely during run 65 and the experiment had to be abandoned (When the engine was opened up, it was found that piston ring failure had occurred resulting in loss of compression and hence unstable power output). The poor mass closures for runs 63, 64 was also probably associated with the poor performance of the engine due to the faulty piston ring. Only run 33 gave a mass balance closure of over 100% (101.45). The closure is however within the range of the majority of the other runs. Run 90 also gave a very poor closure of 77.45%.

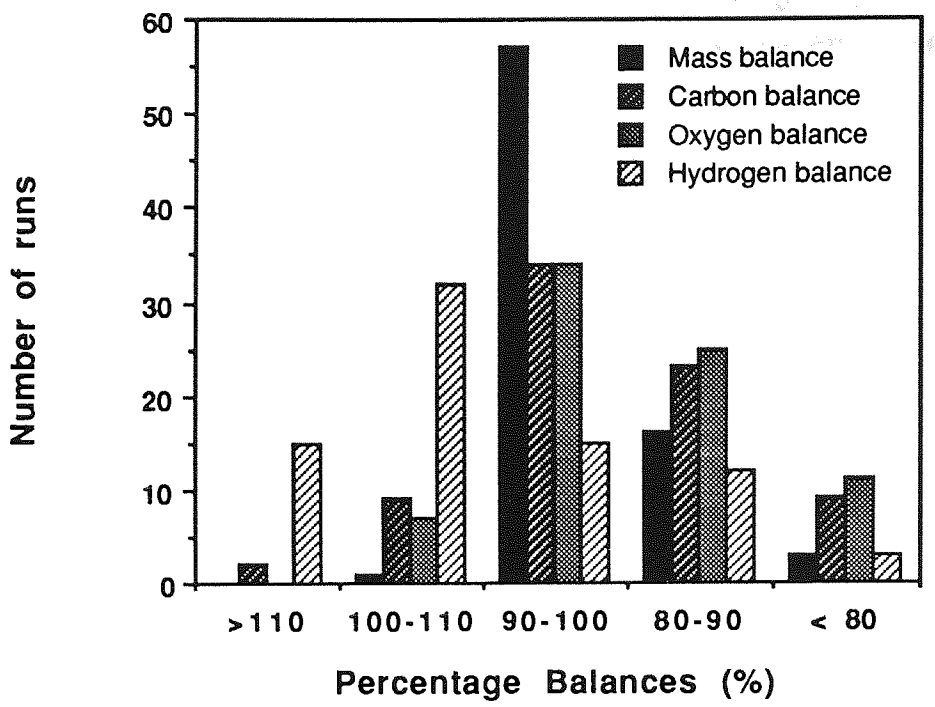


Figure 6.5 Mass and elemental balance closures

Very wet wood (moisture content of 51.5%) was used for run 90 and difficulties were encountered in maintaining the gas quality resulting in poor yields. The same difficulty was encountered in run 96 and the whole run had to be abandoned when the gas quality was not suitable for the engine.

The quality of the overall mass balance was verified by the elemental balance. The average closures for carbon, oxygen and hydrogen were 91.13, 89.30 and 100.35 % respectively. The majority of the carbon balance closures were found to be between 90-100 % and are in the same range of the mass balances analysis. Poor carbon balances were also obtained for runs 29, 47, 55, 56, 62, 63, 64, 91 and 100. The reason for the poor closures for runs 62,63 and 64 has been given earlier. For runs 29, 47, 55, 56, 91 and 100 the poor carbon closures is due to the instability of the gasifier at high throughputs (see section 6.21). However, the relative good overall closure in the carbon balance is probably due to the relative accuracy in collecting char content (from which the majority of the carbon element is derived) as compared to tar and condensate content determinations. The closures for both oxygen and hydrogen indicate a wider closure range. The majority of the oxygen closures range were

between 85-100% while the closures range for hydrogen were found to be greater than 100%. The higher "loss" in both the oxygen and hydrogen elements may be attributed to the uncertainty in the determination of the water content in the condensate collected and the difficulty of collecting tar accurately after the gasifier was cooled down.

Generally, the majority of the mass and elemental balances closures for most of the runs were fairly consistent over a wide range of different operating conditions. The results of the mass balance were comparable with the results of a study by Walawender et al., (1982) with a downdraft gasifier of similar capacity.

6.13 ENERGY BALANCE ANALYSIS

The law of conservation of energy states that the energy entering a predefined control volume is equal to the energy exiting from it. The control volume is the gasifier.

$$\text{Energy balance closure} = \frac{H_{output}}{H_{input}} * 100$$

where, H_{input} = Total energy input into the gasifier
H_{output} = Total energy output from the gasifier

The energy inputs into the gasifier and the energy output from the gasifier is illustrated in Figure 6.6.

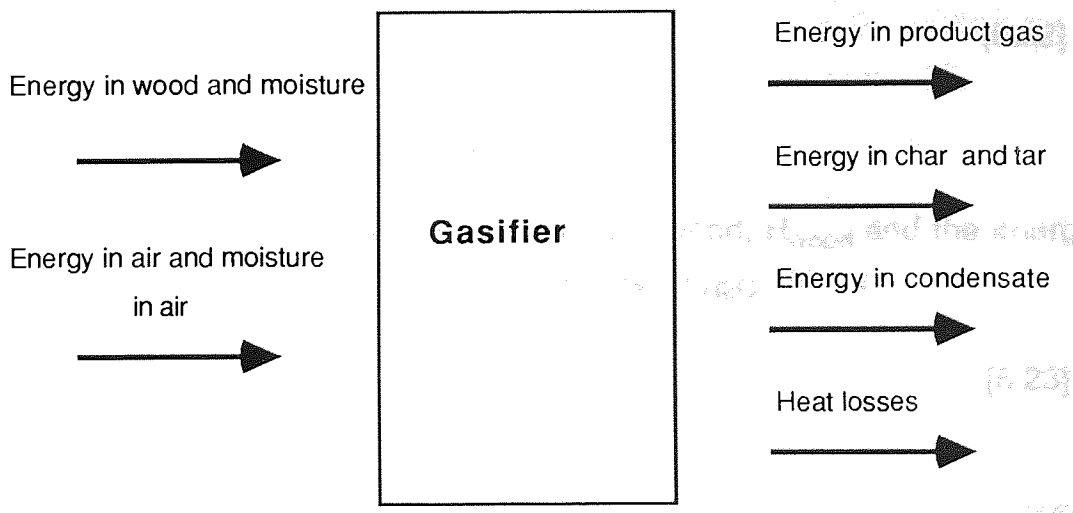


Figure 6.6 Energy balance flow diagram

In the analysis of energy balance, the following assumptions were made:

a) Except for the chemical energy of dry wood input, no direct measurements of the chemical and sensible heat of the other components were made. The respective energy inputs and outputs were estimated in terms of the heat of combustion of the components of each stream, their compositions and temperatures.

b) The gasifier heat losses were mainly through convection and radiation.

c) The reference state is assumed to be liquid water at 32.7 °C so that the higher heating values of the fuel and gases were used in the energy balance calculations.

There are a number of energy balances that are possible for the gasification unit illustrated in Figure 5.7 and 5.8. The relevant energy balances are:

1) Energy balance across gasifier.
2) Energy balance across gasifier,cooling and cleaning system to cold clean gas.
3) Energy balance across the diesel engine.
4) Energy balance across the whole gasifier/engine system.

6.14 ENERGY BALANCE ACROSS GASIFIER

6.14.1 Total energy input H_{input}

The energy inputs to the gasifier are the energy in the wood, H_w and the energy in the air, H_a . Hence,

$$H_{input} = H_w + H_a \qquad [6.22]$$

6.14.1.1 Energy in wood H_w

The energy in wood is the energy of the dry wood, H_{wood} and the energy of the water in the wood in the form of moisture, H_{H2O}. Hence,

$$H_w = H_{wood} + H_{H2O} \qquad [6.23]$$

The energy of the dry wood

$$H_{wood} = H_{c(wood)} + \Delta H_{wood} \qquad [6.24]$$

where, $H_{c(wood)}$ = Chemical energy of dry wood
ΔH_{wood} = Sensible energy of dry wood

Since the higher heating value of rubberwood is used, the moisture content of rubberwood is liquid water, its energy is the sensible heat of water between the inlet temperature T_i of the gasifier and the reference temperature T_r.

By specifying the datum temperature $T_i = T_r = 32.7°C$, then sensible heat of dry wood ΔH_{wood} and $H_{H2O} = 0$

Hence from equation 6.23 and 6.24,

$$H_w = H_{c(wood)} \quad [6.25]$$

$$H_{c(wood)} = HHV_{wood} * F_{wood} \quad [6.26]$$

where, HHV_{wood} = higher heating value of rubberwood
F_{wood} = dry mass flow of wood

Taking, HHV_{wood} = 18436.5 kJ/kg (daf) (from Table 6.8)
F_{wood} = 29.60 kg/h (from Table 6.18)

From equation 6.26,

$$H_{c(wood)} = \frac{18436.5 * 29.60}{1000} \text{ MJ/h} = 545.72 \text{ MJ/h}$$

6.14.1.2 Energy in air Ha

Energy in air is the sensible heat of the dry air and the sensible and latent heat of water contained in the air as moisture.

$$H_a = H_{aw} + \Delta H_{aw} + \Delta H_{air} \quad [6.27]$$

where, H_{aw} = Latent heat of water in air
ΔH_{aw} = sensible heat of water in air
ΔH_{air} = sensible heat of dry air

Since it was specified earlier that $T_i = T_r = 32.7$ °C, then

$\Delta H_{aw} = 0$
$\Delta H_{air} = 0$

Thus, equation 6.27, $H_a = H_{aw}$ [6.28]

From Lewis et al., (1954), the latent heat of water in air at 32.7°C is 2461 kJ/kg.

Hence, the latent heat of water in air is:

$$H_{aw} = F_{aw} * \text{latent heat of water} \quad [6.29]$$

where, F_{aw} = mass flow of water in air.

From Section 6.6.5, F_{aw} = 1.55 kg/h.

Hence, equation 6.29 becomes

$$H_{aw} = \frac{1.55 * 2461}{1000} \text{ MJ/h} = 3.81 \text{ MJ/h}$$

6.14.1.3 Total energy input

From equation 6.22,the total energy input is:

$$H_{input} = 545.72 + 3.81 \text{ MJ/h} = 549.53 \text{ MJ/h}$$

6.14.2 Total energy output of gasifier H_{output}

The energy output of the gasifier is the energy in the product gas, energy in the condensates, tars, char and the heat losses from the gasifier.

Hence, $H_{output} = H_{gas} + H_{water} + H_{tar} + H_{char} + H_{Loss}$ [6.30]

where,

H_{gas} = Energy in raw gas

H_{water} = Energy in water in vapour state

H_{tar} = Energy in tar

H_{char} = Energy in char

H_{Loss} = Heat losses from gasifier.

6.14.2.1 Total energy in product gas H_{gas}

The energy of the product gas is the chemical energy of the dry gas and the sensible heat of the dry gas from the gasifier outlet temperature To to the reference temperature Tr = 32.7°C.

Hence, $H_{gas} = H_{c(gas)} + \Delta H_{gas}$ [6.31]

where, $H_{c(gas)}$ = chemical energy of dry gas
ΔH_{gas} = sensible heat of dry gas.

Chemical energy of dry gas

The chemical energy of dry gas can be calculated as:

$$H_{c(gas)} = Q_{gas} * HHV_{gas} \quad [6.32]$$

where, Q_{gas} = Dry volumetric flow of gas
HHV_{gas} = Higher heating value of gas determined by IGT equation

The IGT equation (Reed, 1982) at STP is given as:

$$HHVgas = 1.055 * (12.1 * X_{H2} + 11.97 * X_{CO} + 37.36 * X_{CH4}) \quad [6.33]$$

where,
X_{H2} = Fractional volume composition of hydrogen
X_{CO} = Fractional volume composition of carbon monoxide
X_{CH4} = Fractional volume composition of methane

Using the gas composition in Table 6.13, in equation 6.33:

$$HHV_{gas} = 1.055 * (12.1 * 0.184 + 11.97 * 0.189 + 37.36 * 0.006)$$
$$= 4.97 \text{ MJ/Nm}^3$$

From Table 6.18, the dry volumetric gas flow,

$$Q_{gas} = 66.75 \text{ Nm}^3/\text{h}$$

Substituting in equation 6.32,

$$H_{c(gas)} = 4.97 * 66.75 \text{ MJ/h} = 332.03 \text{ MJ/h}$$

Sensible heat of gas ΔH_{gas}

The sensible heat of the dry gas is calculated by the following relationship:

$$\Delta H_{gas} = F_{gas} * \Delta H_g \quad [6.34]$$

where, F_{gas} = Mass flowrate of dry gas
ΔH_g = sensible heat of dry gas

The sensible heat in dry gas ΔH_g can be calculated as:

$$\Delta H_g = \int C_{p(gas)}\, dT \quad [6.35]$$

where, $C_{p(gas)}$ is the specific heat capacity of the gas mixture and is a function of the temperature and the composition of the gas shown by the following equation:

$$C_{p(gas)} = A + BT + CT^2 + DT^3 \qquad [6.36]$$

where,

$$A = \sum a_i x_i$$

$$B = \sum b_i x_i$$

$$C = \sum c_i x_i$$

$$D = \sum d_i x_i$$

where a_i, b_i, c_i and d_i are the coefficients of ideal gas specific heat capacities of the i component of the mixture and x_i is the molar fraction of the i component of the mixture.

Combining equation 6.35 and 6.36,

$$\Delta H_g = \int A + BT + CT^2 + DT^3 \, dT \qquad [6.37]$$

By integrating equation 6.37,

$$\Delta H_g = A * (T_o - T_r) + \frac{B * (T_o^2 - T_r^2)}{2} + \frac{C * (T_o^3 - T_r^3)}{3} + \frac{D * (T_o^4 - T_r^4)}{4}$$

From Coulson and Richardson (1977; 1980), the specific heat capacities coefficients are presented in Table 6.20.

Table 6.20
Ideal gas specific heat capacity coefficients

Gas	a	$10^2 * b$	$10^3 * c$	$10^8 * d$
H_2	27.143	0.9273	-1.38	0.7645
CO	30.869	-1.285	2.789	-1.271
CO_2	19.795	7.343	-5.601	1.715
CH_4	19.251	5.212	1.197	-1.131
N_2	31.150	-1.356	2.679	-1.168

C_{pgas} = kJ/molK; T in K

The sensible heat of the dry gas ΔH_g over the temperature range 517.4 K outlet temperature and 305.7 K (reference temperature) is computed by a simple computer programme and is as follows:

$$\Delta H_g = 269.38 \text{ kJ/kg.}$$

Thus the average heat capacity of the dry gas

$$= \frac{269.38}{517.4-305.7} = 1.272 \text{ kJ/kgK.}$$

Substituting in equation 6.34

ΔH_{gas} = 74.83 * 269.38 /1000 MJ/h = 20.15 MJ/h

Substituting into equation 6.31, the total energy of product gas H_{gas}

= 332.03 +20.15 MJ/h = 352.18 MJ/h

6.14.2.2 Total energy of water in vapour state H_{water}

Energy in water in vapour state:

$$H_{water} = H_{\text{water vapour}} + \Delta H_{water} \quad [6.38]$$

where, $H_{\text{water vapour}}$ = energy in water in vapour state

H_{water} = sensible heat of water

Energy in water in vapour state, $H_{\text{water vapour}}$ is:

Enthalpy of steam at 517.4 K - Enthalpy of liquid water at 305.7K

Enthalpy of steam (assumed saturated) at 517.4K

= 2803.36 kJ/kg (Lewis et al., 1954)

Enthalpy of liquid water = 135.05 kJ/kg (Lewis et al.,1954)

Assuming that all the water vapour is condensed into liquid water, the total mass of water output = 10.08 kg/h (see section 6.9)

Energy of water in condensate:

$$= \frac{10.08 * (2803.36-135.05)}{1000} \text{ MJ/h}$$

= 10.08 * 2.668 MJ/h = 26.90 MJ/h

Sensible heat of water, ΔH_{water}

$$\Delta H_{\text{water}} = m_{water} * C_{p(water)} * (T_o - T_r) \quad [6.39]$$

where, m_{water} = Total mass of water output

$C_{p(water)}$ = Specific heat capacity of water at 517.4K

T_o = Temperature at gasifier outlet = 517.4K

T_r = Reference temperature = 305.7K

From steam table, $C_{p(water)}$ at 517.4K =1.954 kJ/kgK

Hence equation 6.39 becomes,

$$\Delta H_{water} = \frac{10.08 * 1.954 * (517.4-305.7)}{1000} \text{ MJ/h}$$

$$= 4.17 \text{ MJ/h}$$

Substituting in equation 6.38,

$$H_{water} = 26.90 + 4.17 \text{ MJ/h} = 31.07 \text{ MJ/h}$$

6.14.2.3 Total energy in tar H_{tar}

Energy in tar, $H_{tar} = H_{tarc} + \Delta H_{tar}$ [6.40]

where, H_{tarc} = Heat of combustion of tar

ΔH_{tar} = Sensible heat of tar

From Table 6.18, the dry mass flow of tar = 0.98 kg/h

Higher heating value of tar (Reed, 1988) = 35.14 MJ/kg

Heat of combustion H_{tarc} = 0.98 * 35.14 MJ/h of tar = 34.44 MJ/h

Sensible heat of tar, ΔH_{tar}

By using the same relationship as in equation 6.39 and taking the average specific heat capacity as 2.73 kJ/kgK (Coulson et al.1980),

Hence, $$\Delta H_{tar} = \frac{0.98 * 2.73 * (517.4-305.7)}{1000} \text{ MJ/h}$$

$$= 0.57 \text{ MJ/h}$$

From equation 6.40, total energy from tar

H_{tar} = 34.44+0.57 MJ/h = 35.01 MJ/h

6.14.2.4 Energy in char, H_{char}

Energy in char, $H_{char} = H_{c(char)} + \Delta H_{char}$ [6.41]

where, $H_{c(char)}$ = Heat of combustion of char

ΔH_{char} = Sensible heat of char

From Table 6.18, the dry mass flow of char = 1.07 kg/h

Taking the higher heating value of char to be 25.26 MJ/h (Reed et al.,1988)

Heat of combustion of char = 1.07 * 25.26 MJ/h = 27.03 MJ

Taking the average heat capacity of char to be 0.652 kJ/kgK (Reed, 1988), and using the same relationship as in equation 6.39,

$$\text{Sensible energy in char} = \frac{1.07 * 0.652 * (517.4-305.7)}{1000} \text{ MJ/h}$$

$$= 0.15 \text{ MJ/h}$$

From equation 6.41, total energy from char

$$= 27.03+0.15 \text{ MJ/h} = 27.18 \text{ MJ/h}$$

6.14.2.5 Heat losses H_{Loss}

To estimate the heat losses from the gasifier it is assumed that the main sources of heat losses are radiation and natural convection. The total heat loss is:

$$H_{Loss} = \sum Q_r + \sum Q_c \qquad [6.42]$$

where, $\sum Q_r$ = Total heat loss by radiation

$\sum Q_c$ = Total heat loss by convection

The heat loss estimations from the gasifier is found in Appendix VIII and result of the total heat loss by radiation and convection are summarised in Table 6.21.

Table 6.21
Gasifier heat losses

Gasifier zones	L_i* (m)	Q_r (MJ/h)	Q_c (MJ/h)
1	0.84	24.95	10.73
2	0.20	9.73	3.42
3	0.74	15.97	7.72
Bottom plate	-	9.30	3.44
Top plate	-	0.14	0.09
Total		60.09	25.40

* Li = height of gasifier zone in m

The total heat loss in equation 6.42 is:

H_{Loss} = 60.09 + 25.4 MJ/h = 85.49 MJ/h

The total heat loss in terms of the chemical energy of wood is:

$$= \frac{85.49}{545.72} * 100 \qquad = 15.66\%$$

The total heat loss in terms of the chemical energy of wood from radiation and convection is:

$$\text{Radiation} = \frac{60.09}{545.72} * 100 \qquad = 11.01\ \%$$

$$\text{Convection} = \frac{25.40}{545.72} * 100 \qquad = 4.65\ \%$$

Determination of radiative and convective heat losses have not been reported in the literature. Kjellstrom reported that the total heat losses in his experiments with a throated downdraft gasifier were in the range of 6.5-15% of wood input (Kjellstrom, 1985). For very large gasifiers (5-10 t/h), the heat loss can be expected to be in the region of 6%. However, for the gasifier of this size, heat losses of about 15% can be considered as reasonable.

From Table 6.22, the heat loss calculated by difference is:

H_{loss} = 549.53-352.18-31.07-35.01-27.18 MJ/h

= 104.09 MJ/h

The total heat loss estimation is about 82.13% of the theoretical heat loss calculated by difference.

In order to investigate the influence of dry wood capacity on the percentage of heat loss (in terms of the chemical energy of wood) from the gasifier, the same runs discussed in section 6.10 were chosen for analysis. The result of the analysis is illustrated in Figure 6.7.

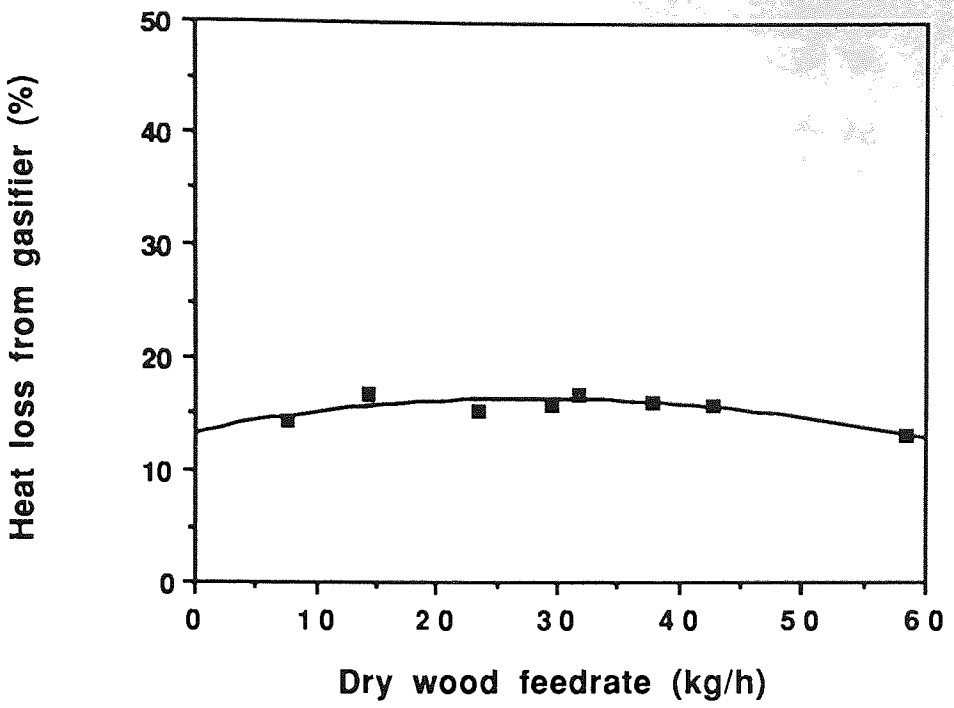


Figure 6.7 Influence of dry wood feedrate on percentage of heat loss from gasifier for runs 22-29

It was found that the dry wood feedrate does not have a very significant influence of the heat loss from the gasifier. The relatively uniform heat loss is probably due to some preheating of incoming air and the cooling of the product gas in the design of the gasifier.

6.14.3 Energy balance data

The energy balance data determined in Section 6.13.1 and Section 6.13.2 is summarised in Table 6.22.

Table 6.22
Energy balance data for run25

Item	Chemical	Sensible	Latent	Total
Wood	542.72	-	-	545.72
Air	-	-	3.81	3.81
Total input				549.53

Table 6.22 continued

Product gas	332.03	20.15	-	352.18
Water vapour	4.17	-	26.90	31.07
Tar	34.44	0.57	-	35.01
Char	27.03	0.15	-	27.18
Total heat losses by radiation				60.09
Total heat losses by convection				25.40
Total energy output				530.89

6.14.4 Energy balance closure across gasifier

$$\text{Energy balance closure} = \frac{H_{output}}{H_{input}} * 100$$

Using data from Table 6.22:

$$\text{Energy closure} = \frac{530.89}{549.53} * 100$$

$$= 96.61\ \%$$

Using the same procedure, the energy closure for the rest of the runs is calculated and summarised in Appendix V.

6.15 OTHER ENERGY BALANCE INDICATORS

Besides the closure of the energy balance, three other energy indicators are widely used in the literature in measuring gasifier performances. They are hot gas efficiency, cold gas efficiency and the raw gas efficiency.

6.15.1 Hot gas efficiency h_{hot}

Hot gas efficiency h_{hot} is defined as:

$$\frac{\text{Energy of hot gas}}{\text{Chemical energy in wood}} * 100$$

Hence,

$$h_{hot} = \frac{H_{c(gas)} + \Delta H_{gas}}{H_{c(wood)}} * 100 \qquad [6.43]$$

6.15.2 Cold gas efficiency h_{cold}

Cold gas efficiency h_{cold} is defined as:

$$\frac{\text{Energy of the cold gas}}{\text{Chemical energy of wood}} * 100$$

Hence,

$$h_{cold} = \frac{H_{c(gas)}}{H_{c(wood)}} * 100 \qquad [6.44]$$

6.15.3 Raw gas efficiency h_{raw}

If the gas is to be used directly in burners without any previous cleaning, it is possible to define the hot gas efficiency of the gas to include the tar in the gas. Thus raw gas efficiency can be defined as:

$$h_{raw} = \frac{H_{gas} + H_{tar}}{H_{c(wood)}} * 100 \qquad [6.45]$$

Using equation 6.43, 6.44 and 6.45, and data from Table 6.22, the relevant energy indicator across the gasifier is:

$$h_{hot} = \frac{332.03+20.15}{545.72} * 100 = 64.53\%$$

$$h_{cold} = \frac{332.03}{545.72} * 100 = 60.84\ \%$$

$$h_{raw} = \frac{332.03+20.15+34.44+0.57}{545.72} * 100 = 70.95\ \%$$

Using the same procedure, the hot gas, cold gas and raw gas efficiencies for the rest of the runs are summarised in Appendix V.

6.16 ENERGY BALANCE ACROSS GASIFIER TO COLD CLEAN GAS

The energy inputs and output across the gasifier to cold clean gas are illustrated in Figure 6.4.

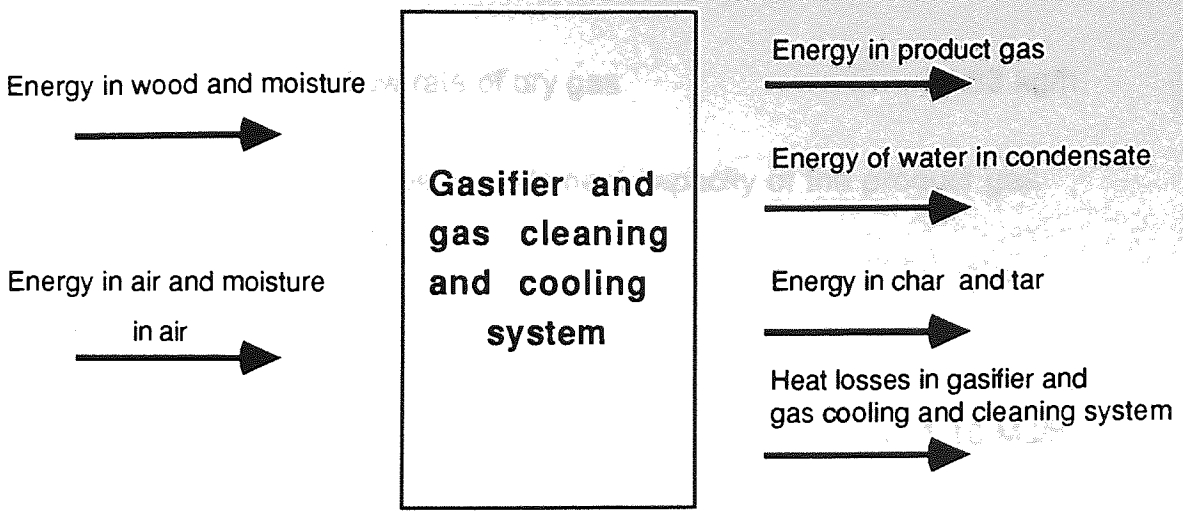


Figure 6.8 Energy balance across gasifier to cold clean gas

From Appendix III, the average outlet temperature of clean gas is 44.3°C or 317.3 K. For the calculations of energy balance across gasifier to cold clean gas, T_o = 317.3K while T_r = 305.7 K (as defined in Section 6.14).

6.16.1 Total energy input H_{Input}

From Table 6.22,
Total input from wood and air = 549.53 MJ/h

6.16.2 Total energy output H_{output}

$$H_{output} = H_{gas} + H_{tar} + H_{char} + H_{water} + H_{Loss} \quad [6.46]$$

6.16.2.1 Energy in product gas H_{gas}

Total energy in the product gas is:

$$H_{gas} = H_{c(gas)} + \Delta H_{gas} + H_{water(gas)} + \Delta H_{water(gas)} \quad [6.47]$$

where,

$H_{c(gas)}$ = Chemical energy of dry product gas
ΔH_{gas} = Sensible energy of dry product gas
$H_{water(gas)}$ = Latent heat of water in gas
$H_{water(gas)}$ = Sensible heat of water in gas

From Table 6.22,

$H_{c(gas)}$ = 332.03 MJ/h

From Table 6.18, mass flow rate of dry gas = 74.83 kg/h

From Section 6.14.2, average specific heat capacity of the product gas
= 1.272 kJ/kgK

Hence, ΔH_{gas} at 317.3K,

$$= \frac{74.83 * 1.272 * (317.3-305.7)}{1000} = 1.10 \text{ MJ/h}$$

From Table 6.18, mass flow of water in gas = 8.40 kg/h
From steam table latent heat of water at 317.3K = 2461 kJ/kg

Hence, latent heat of water in gas $H_{water(gas)}$ at 317.3K is:

$$= \frac{8.40 * 2461}{1000} \text{ MJ/h} = 20.67 \text{ MJ/h}$$

From steam table C_p for water at 317.3K = 1.950 kJ/kgK

Sensible energy of water in gas $\Delta H_{water(gas)}$ at 317.3K is:

$$= \frac{8.40 * 1.950 * (317.3-305.7)}{1000} = 0.19 \text{ MJ/h}$$

Substituting the respective values into equation 6.47,

H_{gas} = 332.03+1.10 +20.67+0.19MJ/h
= 333.13 MJ/h
= 353.99 MJ/h

6.16.2.2 Total energy from tar H_{tar}

From Table 6.22, heat of combustion from tar = 34.44 MJ/h
From Table 6.18, dry mass flow of tar = 0.98 kg/h
From section 6.14.2 (c), average specific heat capacity of tar = 2.73 kJ/kgK
Hence, sensible heat of tar is;

$$= \frac{0.98 * 2.73 * (317.3-305.7)}{1000} \text{ MJ/h} = 0.03 \text{ MJ/h}$$

Total energy from tar H_{tar} is:

= 34.44+0.03 MJ/h = 34.47 MJ/h

6.16.2.3 Total energy from char

From Table 6.22, heat of combustion of char = 27.03 MJ/h
From Table 6.18 dry mass flow of char = 1.07 kg/h
From section 6.14.2 (b), average specific heat capacity of char
= 0.652 kJ/kgK
Hence,sensible energy in char is:

$$= \frac{1.07 * 0.652 * (317.3-305.7)}{1000} \text{ MJ/h} = 0.01 \text{ MJ/h}$$

Total energy from char H_{char} is:
= 27.03+0.01 MJ/h = 27.04 MJ/h

6.16.2.4 Total energy of water in condensate H_{water}

From Table 6.18, mass flow of water in condensate = 1.68 kg/h
From steam tables, latent heat of water at 317.3K = 2461 kJ/kg

Hence, latent heat of water in condensate

$$= \frac{1.68 * 2461}{1000} \text{ MJ/h} = 4.13 \text{ MJ/h}$$

From steam table C_p for water at 317.3K = 1.950 kJ/kgK
Hence sensible energy of water in condensate

$$= \frac{1.68 * 1.950 * (317.3-305.7)}{1000} \text{ MJ/h} = 0.04 \text{ MJ/h}$$

Total energy of water in condensate H_{water}
= 4.13+0.04 MJ/h = 4.17 MJ/h

6.16.2.5 Total heat losses H_{Loss}

The total heat loss is the heat losses from the gasifier and the heat losses across the gas cleaning and cooling system. The total heat loss estimations are found in Appendix VIII and the heat losses are summarised in Table 6.23.

Table 6.23
Summary of estimated heat losses of gasifier system

Components	Estimated heat losses	
	Radiation MJ/h	Convection MJ/h
Pipe from reactor to drum cooler	1.26	1.28
Drum cooler	10.20	6.50
Pipe from drum cooler to box filter	0.88	1.05
Box filter	5.82	5.26
Pipe from box filter outlet to air-cooled condenser	0.80	0.99
Air-cooled condenser	2.49	3.01
Pipe from air-cooled condenser to air-gas mixer	0.44	0.55
Total heat losses	21.89	18.64

Total heat losses from gasifier and gas cooling and cleaning system is:

$$H_{Loss} = 85.49+21.89+18.64 \text{ MJ/h}$$
$$= 125.98 \text{ MJ/h}$$

From equation 6.46,

Total energy output is $= 353.99+34.47+27.04+4.17+125.98$ MJ/h
$= 545.64$ MJ/h

The total heat losses as a percentage of the chemical energy of wood is:

$$= \frac{125.98}{545.72} * 100$$

$$= 23.09\%$$

The total heat loss estimated by difference is:

$= 549.53-353.99-34.47-27.04-4.17$ MJ/h
$= 129.86$ MJ/h

The estimated heat loss is thus 97.01% of the theoretical heat loss by calculation indicating that the heat loss estimation is very reasonable.

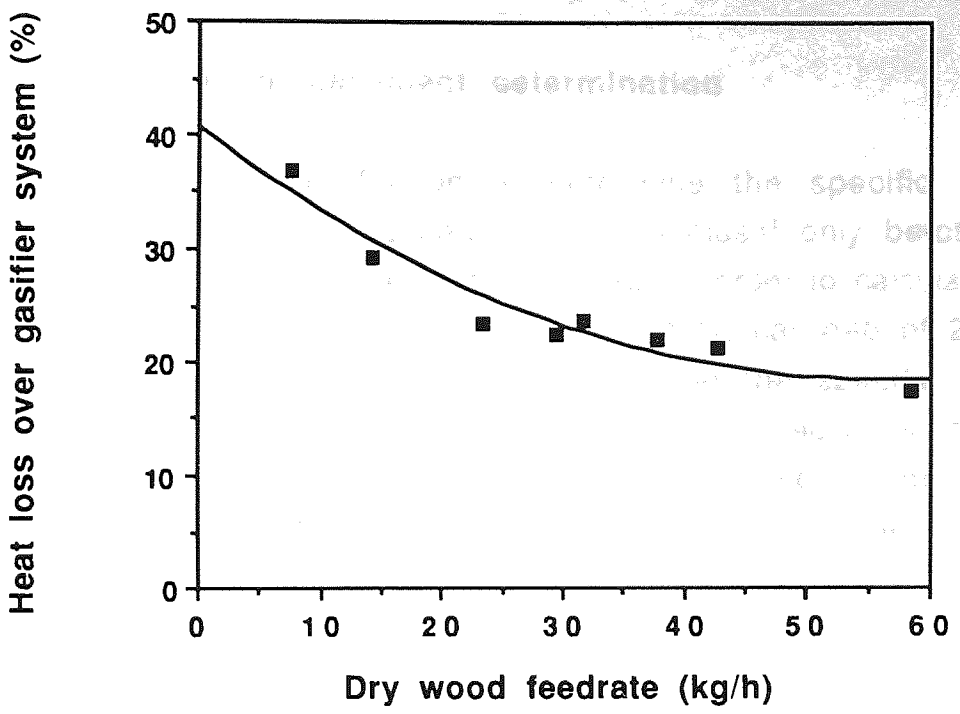


Figure 6.9 Influence of dry wood capacity on heat loss over gasifier system for runs 22-29

The influence of dry wood capacity on heat loss (see section 6.14.2.5) is illustrated in Figure 6.9. It was found that as the dry wood capacity increases, the percentage of heat loss over the gasifier system was found to decrease. Thus the gasifier will have to be operated at higher wood capacity in order to achieve efficiency.

6.16.3 Energy balance closure

$$\text{Energy balance closure} = \frac{545.64}{549.53} * 100$$
$$= 99.29\%$$

The energy closure of the rest of the runs is summarised in Appendix V.

6.17 DIESEL DISPLACEMENT AND THERMAL EFFICIENCY ON DUAL FUEL

6.17.1 Diesel displacement determination

One experiment was performed to determine the specific diesel consumption of the engine generating set on diesel only before the installation of the air-gas mixer (before run 22) in order to calculate the diesel displacement on the respective runs. A typical load of 25 kW electrical output was set in order to determine the specific diesel consumption and the resultant consumption was assumed to be directly proportional to the power output over the range of conditions in the experimental programme. The results of the experiment are given in Table 6.24.

Table 6.24
Trials with 100% diesel

Total running time	6.5 h
Average load	25 kW
Total kWh generated	162.5 kWh
Volume of diesel consumed	60.8 l

From Table 6.24, the specific diesel consumption of the engine for the complete run is:

$$= \frac{60.8}{162.5} \qquad = 0.374 \text{ l/kWh}$$

The extent of diesel displacement with reference to run 25 is summarised in Table 6.25.

Table 6.25
Diesel displacement for run 25

Total operation time	314 mins
Average electrical load	22.8 kW
Total kWh generated	119.32 kWh
Total volume of diesel used	13.8 l

From Table 6.25, volume of diesel used per hour is:

$$= \frac{13.8 * 60}{314} \qquad = 2.64 \text{ l/h}$$

Specific diesel consumption on dual fuel is:

$$= \frac{2.64}{22.8} \qquad = 0.116 \text{ l/kWh}$$

Hence, diesel displacement for run 25 is:

$$= \frac{0.374\text{-}0.116}{0.374} * 100 \qquad = 69.09\ \%$$

The diesel displacement of 69.09% means that 69.09% of the energy to operate the engine was supplied by the producer gas.

Using the same procedure, the diesel displacement of the other runs are summarised in Appendix VI.

6.17.2 Thermal efficiency on dual fuel for power generation

The energy flow diagram is shown in Figure 6.10.

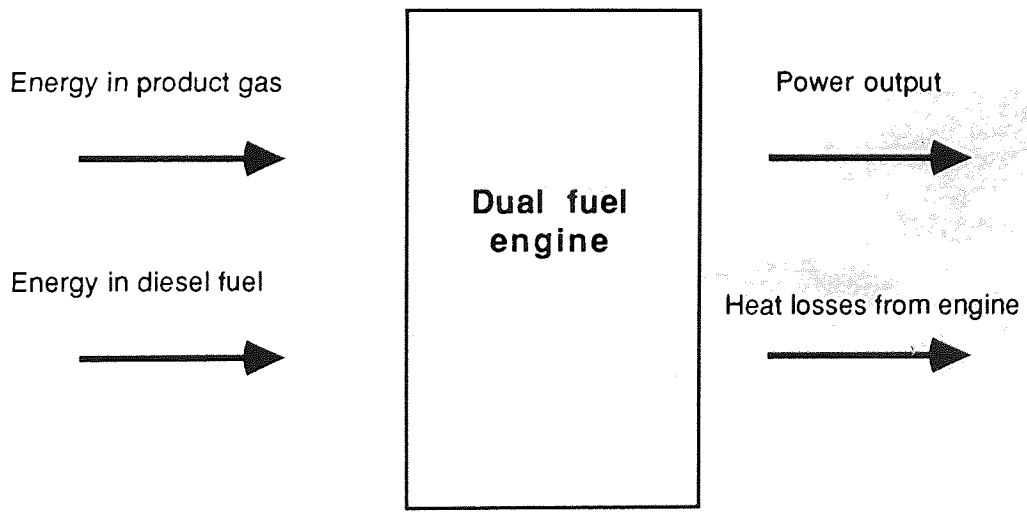


Figure 6.10 Energy flow diagram over dual fuel engine

6.17.2.1 Total energy input Hinput

For dual fuel operation of engines the total energy input is:

$H_{input} = H_{gas} + H_{diesel}$ [6.48]

where, H_{gas} = Total energy from product gas

H_{diesel} = Total energy from diesel

a) Energy from product gas

From Section 6.16.2 (a), H_{gas} = 353.99 MJ/h

b) Energy from diesel

From Section 6.18.1,

Volume of diesel used per hour = 2.64 l/h

The density of diesel used is 0.838 kg/l (UTM, 1989).

Weight of diesel used = 0.838 * 2.64 kg/h

= 2.21 kg/h

The higher heating value of diesel is 45.357 MJ/kg (UTM, 1989).

Hence, total energy from diesel = 45.357 * 2.21 MJ/h

= 100.19 MJ/h

From equation 6.48,

Total energy input, H_{input} = 353.99+100.19 MJ/h

= 454.18 MJ/h

6.17.2.2 Total energy output H_{output}

The energy output is the average power generated, P_{output}.

From Appendix III the average power generated

P_{output} = 22.8 kW

= 22.8 kJ/s

= 82.08 MJ/h

6.17.2.3 Thermal efficiency of engine and heat loss from engine

Thermal efficiency of engine operating on dual fuel is:

$$h_{engine} = \frac{H_{output}}{H_{input}} * 100$$

$$= \frac{82.08}{454.18} * 100$$

= 18.07 %

There are many different values of thermal efficiencies of diesel engines working on dual fuel. They range from 15-40% (Kjellstrom, 1980; Dennetiere et al., 1980; Vyarawalla et al., 1984; Monford, 1982). However, it is difficult to compare the values as they are conditional rather than typical because the engine loads are not stated.

The thermal efficiencies of each of the runs are summarised in Appendix V.

From section 6.17.2.1, $H_{Loss(engine)}$ = 454.18 - 82.08 MJ/h
= 372.10 MJ/h

6.18 ENERGY BALANCE OVER WHOLE SYSTEM

The energy balance over the whole system is illustrated in Figure 6.11.

6.18.1 Total energy input H_{input}

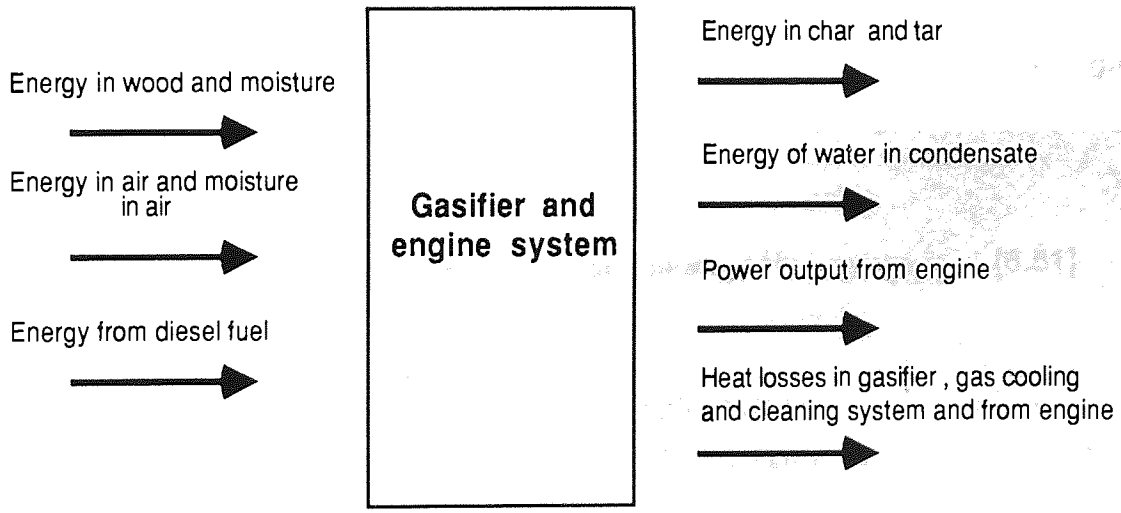


Figure 6.11 Energy balance diagram over whole system

The total energy input over the whole system is:

$$H_{input} = H_{wood}+H_{diesel} \quad [6.49]$$

From Table 6.22,
Total energy inputs from wood and air is:

$$H_{wood} = 549.53 \text{ MJ/h}$$

From Section 6.17.2,

Total energy input from diesel is:

$$H_{diesel} = 100.19 \text{ MJ/h}$$

Substituting the respective values into equation 6.49,

$$H_{input} = 549.53 + 100.19 \text{ MJ/h}$$
$$= 649.72 \text{ MJ/h}$$

6.18.2 Total energy output H_{output}

The total energy output over the whole system is:

$$H_{output} = H_{tar}+H_{char}+H_{water}+\sum H_{Loss}+P_{output} \quad [6.50]$$

From section 6.16 (b), (c) and (d),
Total energy from tar, char and water in condensate is:

$$= 34.47 + 27.04 + 4.17 \text{ MJ/h}$$
$$= 65.68 \text{ MJ/h}$$

The total heat losses $\sum H_{Loss}$ is the heat losses over the gasifier, gas cleaning and cooling system and the heat losses in the engine.

Hence,

$$\sum H_{Loss} = H_{Loss(gasifier)}+H_{Loss(cleaning\ and\ cooling)}+H_{Loss(engine)} \quad [6.51]$$

From Table 6.23,

$H_{Loss(gasifier)}+H_{Loss(cleaning\ and\ cooling)} = 125.98$ MJ/h

From section 6.17.2.3, $H_{Loss(engine)} = 372.10$ MJ/h

Substituting the relevant values into equation 6.51,

$$\sum H_{Loss} = 125.98+372.10 \text{ MJ/h}$$
$$= 498.08 \text{ MJ/h}$$

From Section 6.18.2, $P_{output} = 82.08$ MJ/h

Substituting all the relevant values into equation 6.50,

$$H_{output} = 65.68+498.08 + 82.08 \text{ MJ/h}$$
$$= 645.83 \text{ MJ/h}$$

6.18.3 Energy balance closure

Energy balance closure over the whole system is:

$$= \frac{H_{output}}{Hi_{nput}} * 100$$

$$= \frac{645.83}{649.72} * 100 = 99.40\ \%$$

Using the same method of calculation, the energy closures for the rest of the runs are summarised in Appendix VI.

6.19 ENERGY BALANCE ANALYSIS

The results of the energy balance analysis are summarised in Table 6.26 and are represented in Figure 6.12. If the mass balance closure is good, then the main source of uncertainty in the energy balance is the estimation of the heat losses. The heat losses from the gasifier and the gas cooling and cleaning system were assumed to be radiative and convective. They were estimated in terms of an assumed temperature profile along the gasifier and an estimated surface temperature. The estimated heat losses from the gasifier for run 25 accounted for 15.85 % of the chemical energy of wood. If cold clean gas is obtained, the total heat loss accounted for 22.47 % of the chemical energy of wood.

Table 6.26
Energy balance closures

Closures, %	Over gasifier	Over cold,clean gas	System
>110	6	15	13
100-110	25	27	29
90-110	38	28	29
80-90	5	4	4
<80	3	3	2
Average	98.89	101.52	101.20

From Table 6.26, poor energy balances of less than 80 % over the gasifier were obtained for runs 62, 63, 64 for the same reasons discussed earlier. Six other runs (runs 51, 52, 53, 88, 89 and 90) had energy closures of between 111-120 %. Runs 51, 52, 53, and 88 all have good mass balance

of between 90-100 % and hence the main reason for the high energy closure is due to a higher estimation of heat losses. Run 90 has poor mass balance closure and hence a poor energy balance closure is expected. Run 89 gave a poor energy balance closure probably for the same reason.

The poor energy closures over cold clean gas and over the whole system are also for the same runs that gave poor energy closures over the gasifier. Overall, all three energy balances in Table 6.26 yielded comparable average values.

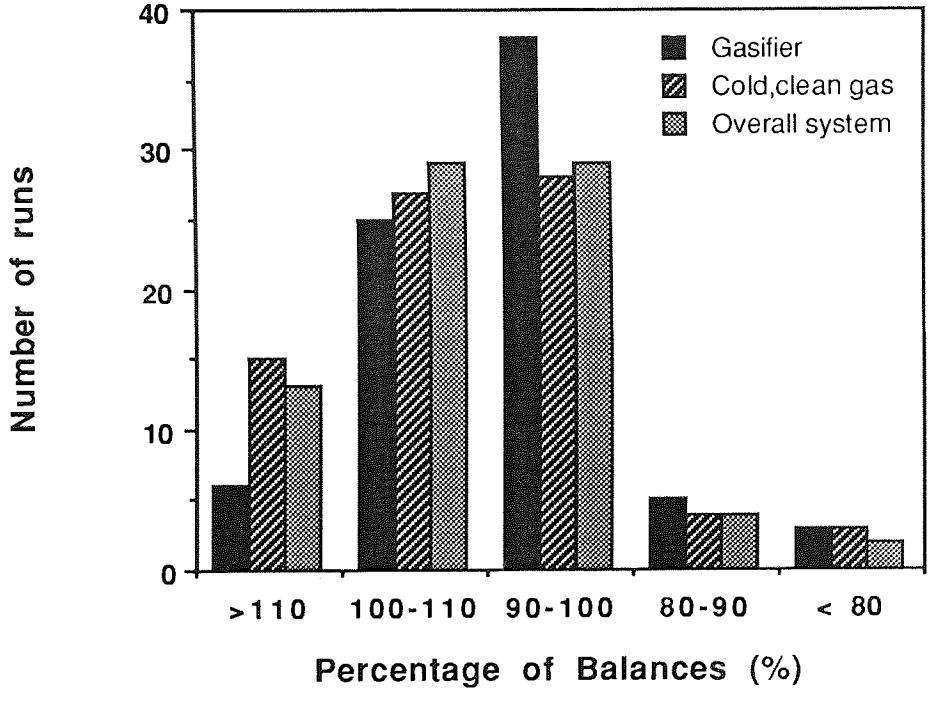


Figure 6.12 Energy balances closures

6.20 COMPARISON WITH OTHER WORK

6.20.1 The Aston Carbon Boundary Model

This model is described in detail by Double 1988. The system is modelled to represent three situations of pyrolysis dominant (when pyrolysis carbon accumulates in the bed); equilibrium or carbon boundary operation (when the rate of carbon production from pyrolysis just balances the rate of char gasification which is the thermodynamic optimum); gasification dominant

when the rate of carbon consumption exceeds the rate of production and thus the gasifier operates with an excess of air as occurs in most gasifiers.

The model employs thermodynamic equilibrium relationships to predict gas compositions which can be empirically modified to to account for pyrolysis products in the product gas. The model requires the inputs of carbon, hydrogen, oxygen, moisture content and heat loss. The gasifying agent requirement is calculated by the model, although its inlet temperature has to be specified. Operating conditions from run 25 were input to predict the gas composition and compare it with achieved results- see Table 6.27.

Table 6.27
Model Predictions and Gasifier Performance

Parameters		Model	Actual run
Heat loss (%)		15.0	15.85
Gas composition (% vol)	H_2	17.1	18.4
	CO	13.1	12.3
	CO_2	15.8	18.9
	CH_4	1.1	0.6
	N_2	51.5	49.8
	H_2O	7.6	na

* gas exit temperature, na = not available

The model works on a basis of 100 % carbon conversion to gas with no tar and char being produced. In actual operation tar and char is being produced and accounts for for 2.7 % (based on weight of gas yield), thus reducing the overall gas yield and reducing the carbon available for conversion to carbon monoxide. The differences in the hydrogen and methane composition could be accounted for in the water content of the gas which was not measured during the research.

6.20.2 Comparison with other work

Performance data on other downdraft throated gasifiers was collected from a number of references to compare the performance of the rubberwood gasifier. The performance data is summarised in Table 6.28. Data were collected from a number of different reactors which covers a number of different wood species and variations in reactor design and operations. Of

the data collected, the system that is most directly comparable to the rubberwood gasifier is the unit reported as the Twente throated gasifier. It can be seen that the unit operates at a higher specific capacity than the rubberwood gasifier because of different reactor and grate design. However, the gas composition and heating value data is comparable with the rubberwood gasifier system.

The tar content of the product gas is 0-0.25 g/Nm^3. The tar content of the product gas for run 25 was not measured but tar contents of the product gas from runs 74-101 indicate that the tar content of the product gas is 0.950-1.450 g/Nm^3. This range is considerably higher than that of Cogliali's report. The reason for the lower tar content of the Cogliali gasifier is that it is operated at a higher temperature which facilitates better tar cracking. However it is difficult to draw any conclusions about the tar contents of other systems due to the lack of data and different methods of measuring tar contents of product gas. However, the gas yield per dry kilogram of wood is comparable to that of the rubberwood gasifier.

From the data presented in Table 6.28, it can also be concluded that throated systems have tight control on the properties of the fuel and have limited scale-up limitations. In general, all the throated systems surveyed tend to use fuels which are large in size and have low moisture content (less than 30 %) in order to minimise the problem of air jet penetration (see chapter 4). None of the throated systems have successfully gasified rice husk although Energy Equipment Engineering has managed to gasify a mixture of sawdust and wood chips in a throated system (Groeneveld et al., 1983). It can therefore be concluded that throated gasifiers are very fuel specific.

Table 6.28 also indicates that the largest throated gasifier available is of the order of 560 kg/h for the Pillard system reported by Bridgwater et al., 1986. Larger systems have, however, been reported although not in detail (Bridgwater et al., 1986). The scale-up potential of throated gasifiers is therefore limited compared with an open core system where systems of up to 900 kg/h have been reported (Graboski and Brogan, 1987; Bridgwater et al., 1986). However, throated systems can be operated at specific capacities of up to 3800 dry kg/m^{2}h indicating a rapid reaction at the throat.

Table 6.28 Comparison of results from various throated downdraft gasifiers

Name Type	FRIM (Run25) Throated	Twente Throated	UCD Throated	Duvant Throated	Groenevald Throated	FW Throated	Imbert Throated
Grate diameter, mm	20.2	65	89	na	na	na	na
Specific gasification capacity, dry kg/m^{2}h	943	1000-2500	3150-3800	450	32	100	600
Feedstock							
Type	Wood chips	Wood chips	Wood chips	Wood chips	Wood chips	Wood chips	na
Moisture content , %dry	11.5	13.0	9.9	max 25	10.0	20	25
Size (mm)	30x30x10	na	0-25.4	13x75x75	18	30-100	80
Operation							
Pressure, bar	1.0	1.0	1.0 1.0	1.0	1.0	1.0	1.0
Oxidation temperature,°C	800-900	1327	850-1050	na	na	900	na
Gas composition % volume cold and dry							
H_2	18.4	17.4	15.9	17.5	18.6	18.0	16.5
CO	18.9	18.5	23.6	15.5	17.1	23.0	20.5
CO_2	12.3	12.0	11.4	14.5	14.4	10.0	10.0
CH_4	0.6	1.1	3.4	2.0	2.3	2.0	1.5
N_2	49.8.	51.0	45.7	50.5	47.6	47.0	50.5
HHV dry, MJ/Nm^3	4.97	5.00	5.73-6.15	4.65	4.33	4.7	4.8
Gas yield (dry Nm^3/kg)	2.53	2.98	2.0-2.4	na	na	2.1	na

Table 6.28 continued **Comparison of results from various throated downdraft gasifiers**

Name Type	Vyncke Throated	UF Throated	Forintek Throated	Forintek Throated	Forintek Throated	Pillard Throated	UCD Throated
Grate diameter, mm	na	63.5	na	na	na	na	177
Specific gasification capacity, dry kg/m^{2}h	20	1800-2200	60.8	48.4	56.3	560	22.8
Feedstock							
Type	Wood chips	Wood chips	Wood chips	Wood chips	Wood chips	Wood chips	Waste
Moisture content , %dry	33	5.3-13.6	3.6	4.2	6.2	max 30	5.8
Size (mm)	50	na	12.7-25.4	12.7-25.4	4.8-12.7	6-200	na
Operation							
Pressure, bar	1.0	1.0	1.0	1.0	1.0	1.1	1.0
Oxidation temperature,°C	na	na	na	na	na	na	na
Gas composition % volume cold and dry							
H_2	16.3	16.3	16.9	20.0	9.0	11.0	12.5
CO	20.8	20.8	23.0	25.5	8.3	19.0	16.5
CO_2	10.5	10.5	8.1	7.8	7.6	12.0	8.0
CH_4	1.9	1.9	2.8	2.7	1.3	2.5	1.9
N_2	49.0.	49.0	44.1	40.9	64.7	51.5	58.1
HHV dry, MJ/Nm^3	5.46	5.46	6.63	7.23	3.24	4.80	4.19
Gas yield (dry Nm^3/kg)	na	na	na	na	na	na	1.75

Sources of information for Table 6.28

FRIM	Rubberwood gasifier used in the experimental programme.
Twente	Cogliali, (1986). Advanced Gasification - "Methanol Production from Wood - Results of the EEC Pilot Programme ", Beenackers AACM and Van Swaiij WPM (eds), (D.Reidel Publishing Company, Dordecht, Holland, 1986).
UCD	Goss JR and Lamorey GW (1982). "Gasification characteristics of chips fro beached logs sawmill residues in Southeast Alaska, USDA Report No. PNW-82-49.
Duvant	Bridgwater et al., (1986). "Technical and Market Assessment of Biomass Gasification in the UK". Report to ETSU, UKAEA, Harwell, United Kingdom.
Groenevald	Groenevald et al., (1983). "Production of tar free gas in an annular co-current moving bed gasifier". In "Energy from Biomass and Wastes".
FW	Same source as Duvant.
Imbert	Same source as Duvant.
Vyncke	Same source as Duvant
UF	Crane TH (1979). "Production of low Btu gas via a downdraft gasifier". Texas Forest Products Laboratory, USA.
Forintek	Winship R (1980). "Evaluation of Fuels for operation of a fixed bed downdraft commercial gasifier". Canadian Bioenergy R and D Seminar, Volume 2.
Forintek	Same as reference above.
Forintek	Same as reference above.
Pillard	Same source as Duvant.
UCD	Vigil SA and Tchobanoglous G, (1982). "Cogasification of densified sludge and solid waste in a downdraft gasifier". Report for US Environmental Protection Agency. Report No. EPA/600/2-82-047.

6.21 PERFORMANCE EVALUATION OF THE GASIFIER

The performance of the gasifier is evaluated by the heating value of the product gas, the cold gas efficiency and power output of the engine since the objective of the gasifier system is to generate electricity by dual fuel engine. The main parameters investigated are:

The influence of wood moisture and particle size on gasifier performance

The influence of moisture is important because the high humidity in the tropics often results in wood of high moisture content. Particle size is important because of the varying sizes in which rubberwood residues are generated in Malaysia.

The ability of the gasifier to turndown in terms of dry wood capacity

Turndown of the gasifier is important for applications because different load changes are required in the commercial application of the gasifier. The investigation of turndown will also provide information on the scale-up potential and limitations of the gasifier.

The overall tar cracking efficiency of the gasifier

The overall tar cracking efficiency of the gasifier is investigated through better air distribution by the use of more air nozzles or by the creation of a higher reaction zone temperature through the reduction in throat diameter are also investigated. Efficient tar cracking in the gasifier will minimise the need for elaborate downstream gas cleaning and cooling systems.

The influence of dry wood capacity and power output on dual fuel

The main purpose of dual fuelling is to achieve maximum diesel displacement under stable engine operation. The influence of dry wood capacity and power output of dual fuel engine on diesel displacement is also investigated. The performance of the dual fuel engine is investigated in terms of the thermal efficiency of the engine.

Mass and energy balances for runs 1-21 were not performed as these were treated as commissioning runs and some data was not collected. As a result, data for runs 1-21 are not analysed in this thesis.

6.21.1 Influence of moisture content of rubberwood on gasifier performance

6.21.1.1 Data selection

The data selected for analysis are only based on two wood sizes namely 3 cm x 3 cm x 1 cm and 3 cm x 3 cm x 3 cm. Wood of other sizes are not analysed because of the lack of sufficient data. All data are selected from Appendix III, IV and V. In the experimental programme, it was planned that the influence of moisture content on gasifier performance would be investigated with a constant dry wood capacity. However due to the difficulty in gasifying wood at high moisture content, the dry wood capacity could not be kept constant for some of the runs selected for analysis. As a result, some influence of different dry wood capacity is expected to affect the analysis of the influence of moisture content on gasifier performance. Data selected for the analysis are summarised in Table 6.29.

Table 6.29
Influence of moisture content of rubberwood on gasifier performance

Runs	Dry wood capacity kg/h	Moisture content % wet	Cold gas efficiency %	Gas heating value MJ/Nm^3	Power output kWe
25	29.60	10.3	60.48	4.97	22.8
26	31.72	9.8	63.61	5.20	25.7
88	26.73	31.3	55.79	4.26	19.7
89	41.67	41.6	43.60	3.67	17.3
90	48.31	51.5	46.19	3.05	16.1
41	25.62	10.3	47.90	5.43	15.9
42	31.43	9.6	52.72	5.98	21.3
92	32.47	18.6	40.08	4.13	18.9
93	25.94	31.6	42.00	3.55	17.6
94	22.93	43.5	38.31	2.95	16.4

6.21.1.2 Data analysis

The results of the analysis are summarised in Figure 6.13, 6.14, 6.15, 6.16 and 6.17. (All the graphs presented are selected based on the best R^2 values).

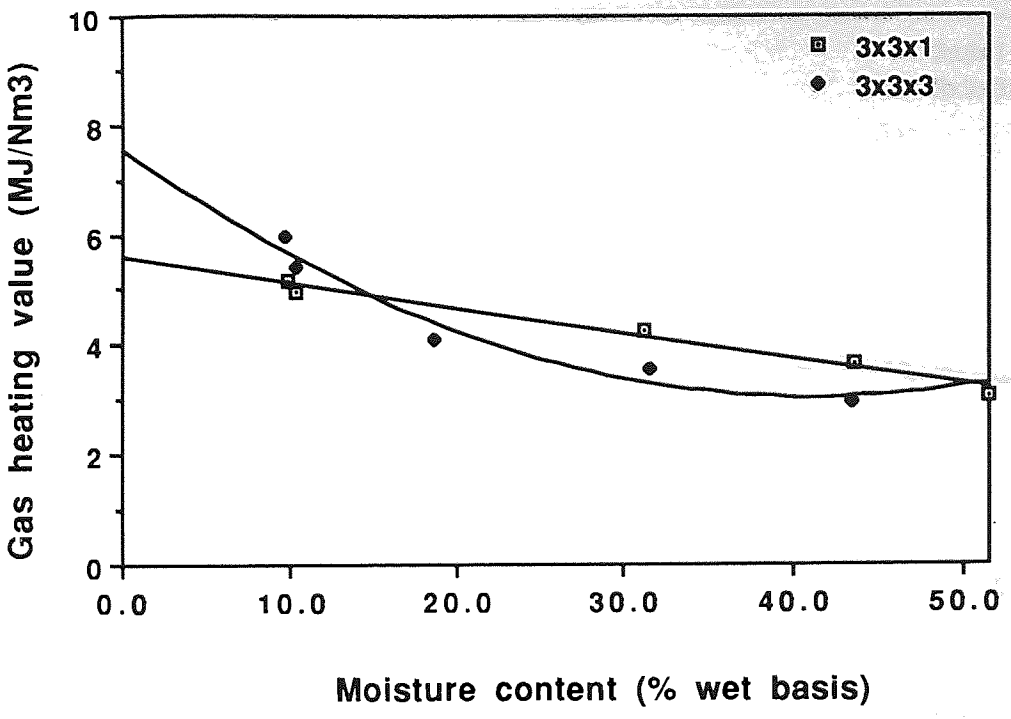


Figure 6.13 Influence of moisture content of wood on gas heating value

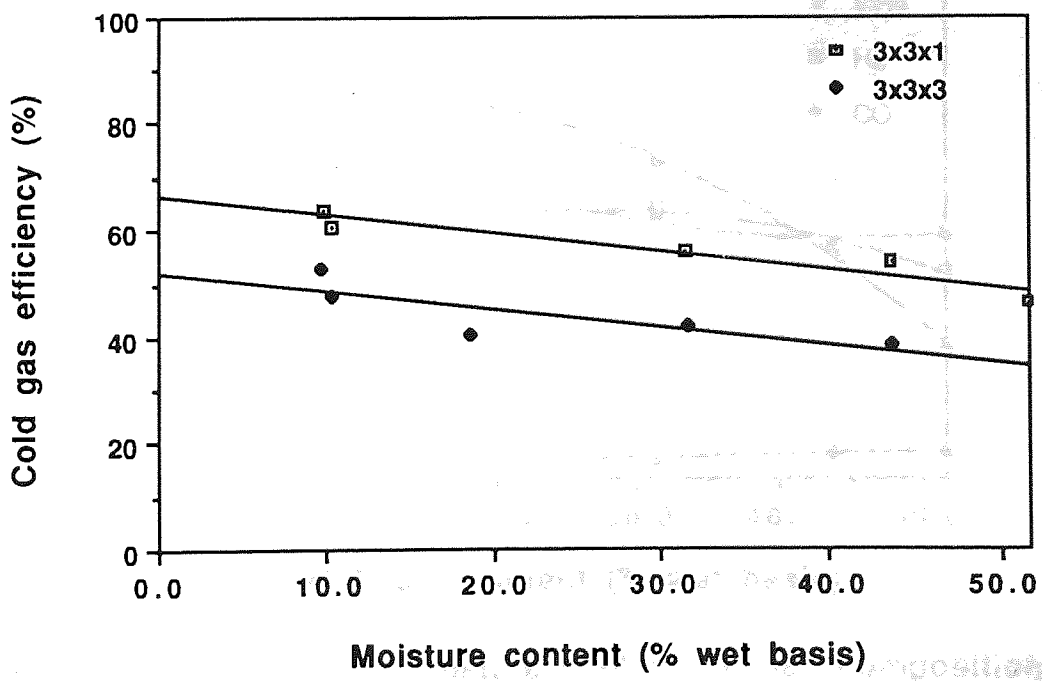


Figure 6.14 Influence of moisture content on cold efficiency

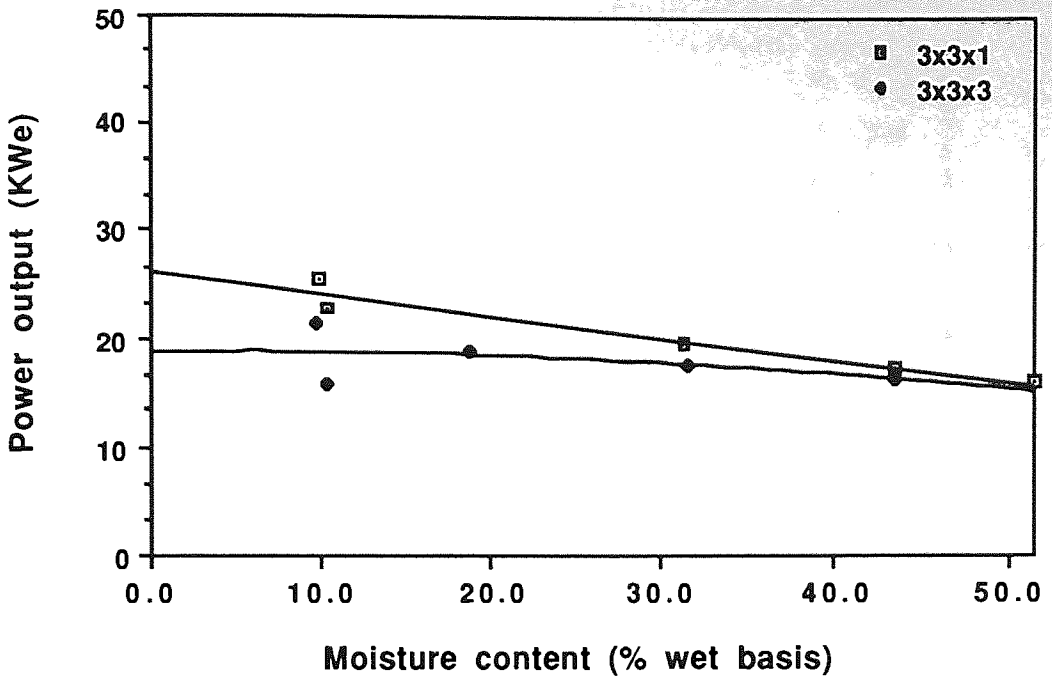


Figure 6.15 Influence of moisture content on power output

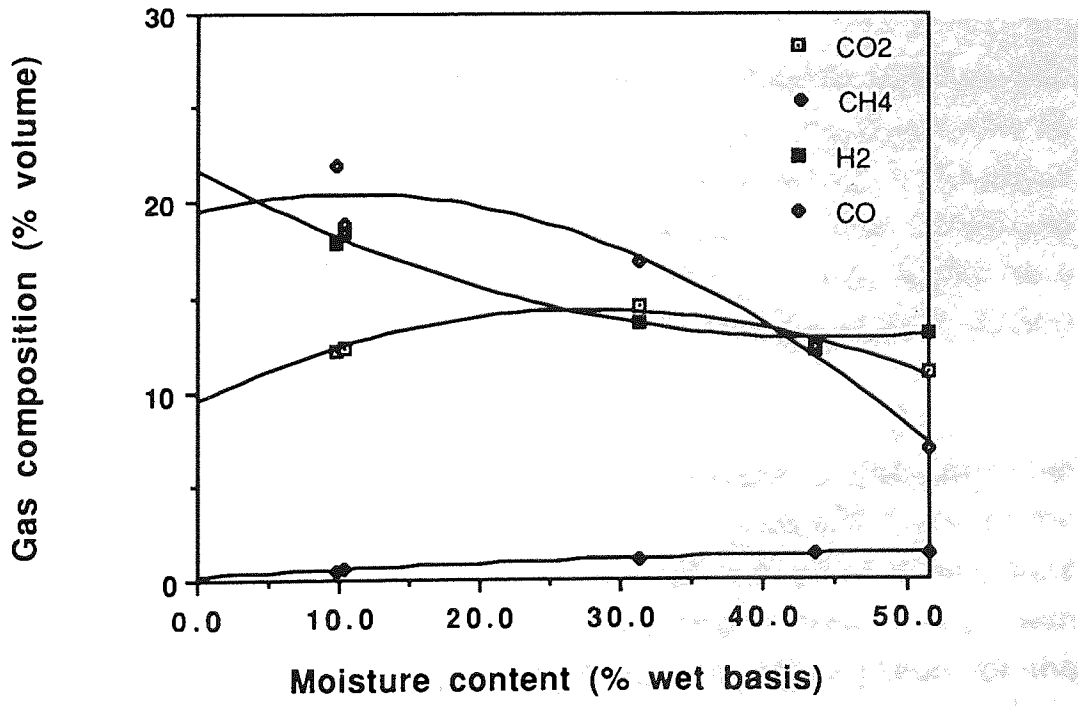


Figure 6.16 Influence of moisture content on gas composition for size 3cm x 3cm x 1cm

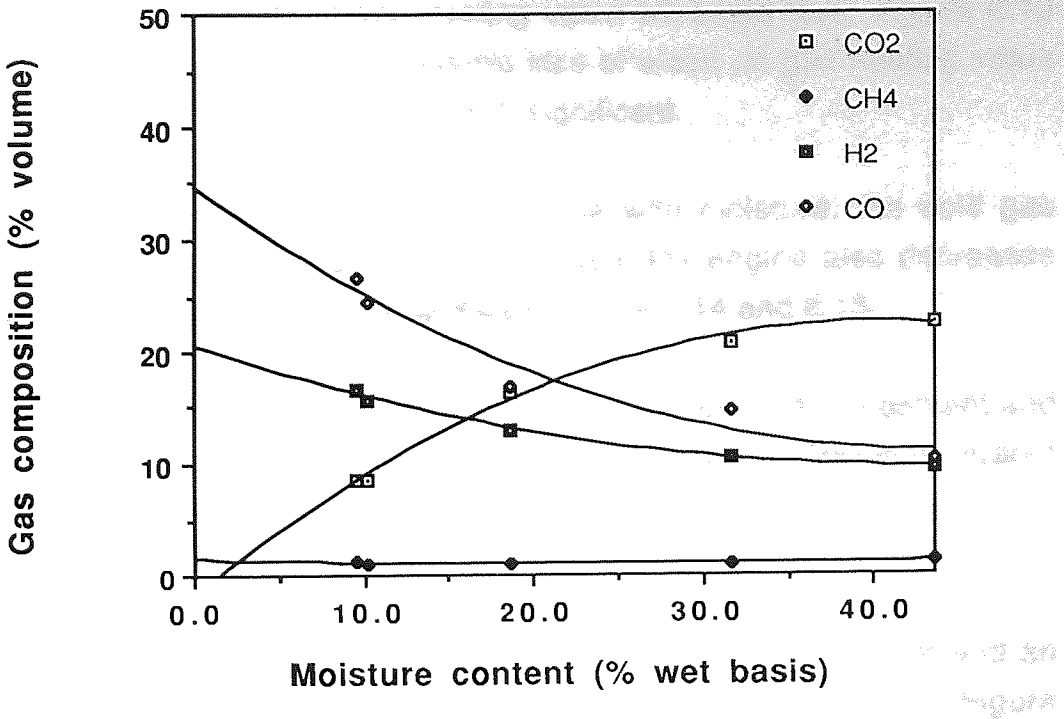


Figure 6.17 Influence of moisture content of wood on gas composition for wood 3cm x 3cm x 3cm

The effect of moisture content on gas quality is somewhat controversial. Jenkins, (1980) for example, reported that a moisture content of less than 20 % wet basis is necessary for wood to be used successfully in downdraft producer gas systems, while various other sources such as Graf, (1989) and Susanto, (1989) reported that reliable operation and good gas quality were achieved in downdraft gasifiers using moisture contents of up to 40 % (wet basis).

Figure 6.13 , shows that the gas heating value decreases as moisture in the feed increases. Increasing the moisture content of wood will decrease the sensible energy of the product gas since more heat is required to evaporate water from the wet wood. The decrease in the gas heating value with moisture is attributed to the extra latent heat of vapourisation for the increased amount of moisture in the feed. This heat in practice is never recovered. Rambush, (1923) reported that the heat loss due to moisture content can be from 2-15 % of the higher heating value of the wood as moisture increased from 10-50 % (wet basis). However, contrary to most cited literature, it was found that it is possible to gasify wood with moistures

of up to 51.5 % (wet basis), although the economics of using wood with such a high moisture content is questionable. Igniting the wood becomes increasingly difficult and the gas heating value becomes low. Figure 6.13 also shows that the influence of particle size of wood on gas heating value as moisture content increases is not very significant.

Due to a decrease in the gas heating value with moisture, the cold gas efficiency of the gasifier and power output from the engine also decreases as moisture increases. This is illustrated in Figure 6.14 and 6.15.

Higher moisture contents of wood will result in a decrease in CO content and an increase in CO_2 and H_2 content as moisture increases. This is illustrated in the following water shift reaction:

$$H_2O + CO = CO_2 + H_2$$

The water shift reaction is evident from the decrease in CO content and an increase in CO_2 as moisture in wood increases (Figure 6.16 and Figure 6.17). The water shift reaction will also result in a corresponding increase in H_2 content. However, the H_2 content for both sizes decreases as moisture in wood was increased. It is postulated that the part of the hydrogen may have been combusted in the gasification zone to supply the extra heat necessary to evaporate the extra moisture in wood at high moisture content.

For wood of size 3 cm x 3 cm x 1 cm, the gas composition is also influenced by the effect of different dry wood flow rates. From Figure 6.16, it can also be concluded that at moisture contents greater than 40 %, the effect of higher dry wood flow rate is probably more dominant than the water shift reaction. This is evident from the increased in CH_4 content indicating a decrease in thermal cracking of hydrocarbons and higher tar yields at higher temperature (see section 6.21.2).

6.21.2 Influence of dry wood capacity on gasifier performance

6.21.2.1 Data selection

Three representative sizes are chosen for analysis. The sizes chosen are 3

cm x 3 cm x 1 cm to represent the smallest size, 3 cm x 3 cm x 3 cm to represent the intermediate size and 3 cm x 3 cm x 6 cm to represent the largest size. The average moisture content of rubberwood for all the runs selected is 10 %. The data selected is summarised in Table 6.30.

Table 6.30
Influence of dry wood capacity on gasifier performance

Runs	Wood size cmxcmxcm	Dry wood capacity kg/h	Cold gas efficiency %	Gas heating value MJ/Nm3	Power output kWe
22	3 x 3 x 1	7.64	48.97	3.51	4.6
23	3 x 3 x 1	14.38	50.74	4.01	9.3
24	3 x 3 x 1	23.51	57.12	4.39	17.4
25	3 x 3 x 1	29.60	60.48	4.97	22.8
26	3 x 3 x 1	31.72	63.61	5.20	25.7
27	3 x 3 x 1	37.77	58.24	4.99	28.5
28	3 x 3 x 1	42.75	53.69	5.26	26.1
29	3 x 3 x 1	58.46	39.37	5.53	23.8
39	3 x 3 x 3	9.45	43.46	4.75	5.3
40	3 x 3 x 3	18.57	48.75	5.07	10.8
41	3 x 3 x 3	25.62	47.90	5.43	15.9
42	3 x 3 x 3	31.43	52.72	5.98	21.3
43	3 x 3 x 3	37.99	53.86	6.17	26.5
44	3 x 3 x 3	44.85	57.77	6.47	30.5
45	3 x 3 x 3	49.72	63.74	6.32	33.5
46	3 x 3 x 3	57.74	58.83	6.42	28.2
47	3 x 3 x 3	67.42	41.88	6.43	22.7
66	3 x 3 x 6	21.56	41.66	4.14	11.0
67	3 x 3 x 6	28.96	43.03	4.46	16.2
68	3 x 3 x 6	33.98	48.16	4.67	21.3
69	3 x 3 x 6	40.83	50.69	4.63	25.8
70	3 x 3 x 6	46.82	52.18	4.61	26.8
71	3 x 3 x 6	53.07	52.68	4.61	23.3
72	3 x 3 x 6	60.70	43.22	4.31	19.8
73	3 x 3 x 6	67.50	43.00	4.36	14.2

6.21.2.2 Data analysis

The results of the analysis is summarised in Figure 6.18, 6.19, 6.20, 6.21, 6.22 and 6.23.

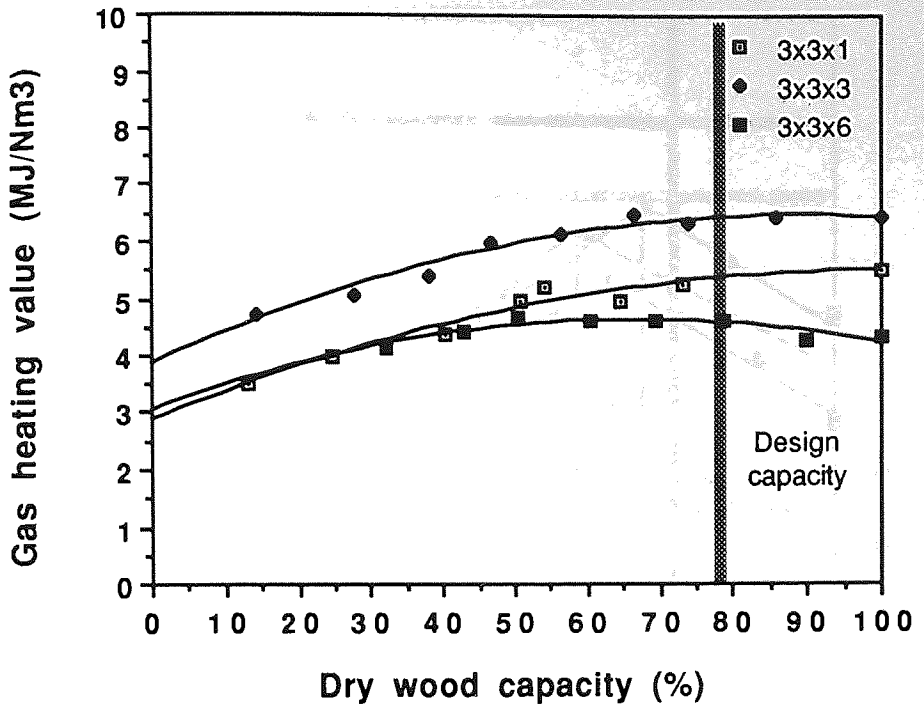


Figure 6.18 Influence of dry wood capacity on gas heating value

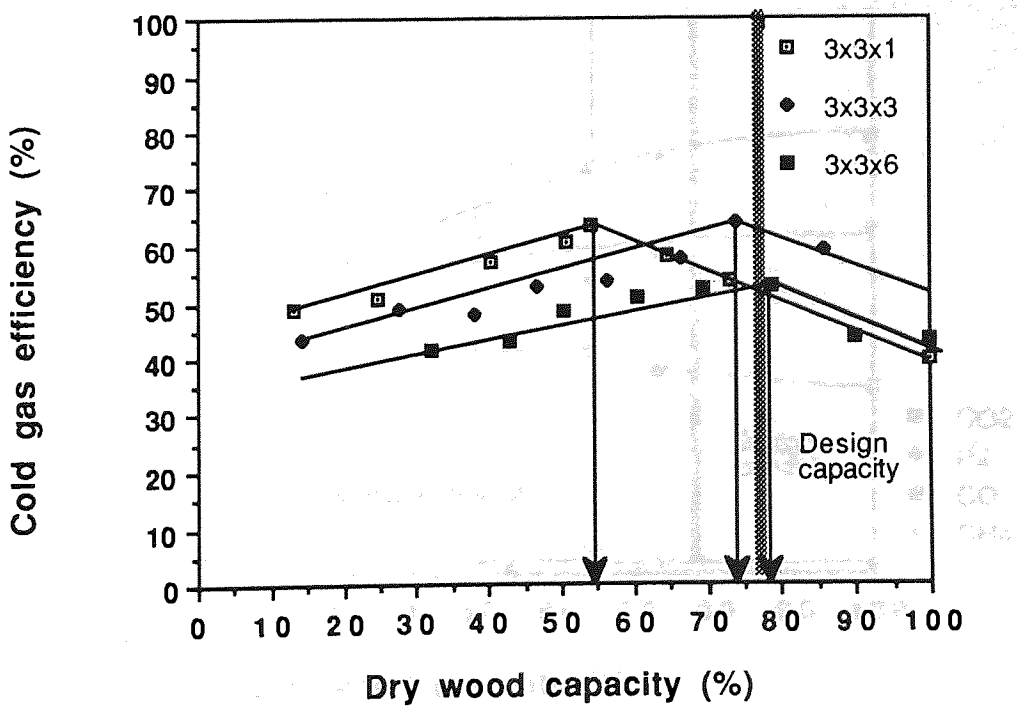


Figure 6.19 Influence of dry wood capacity on cold gas efficiency

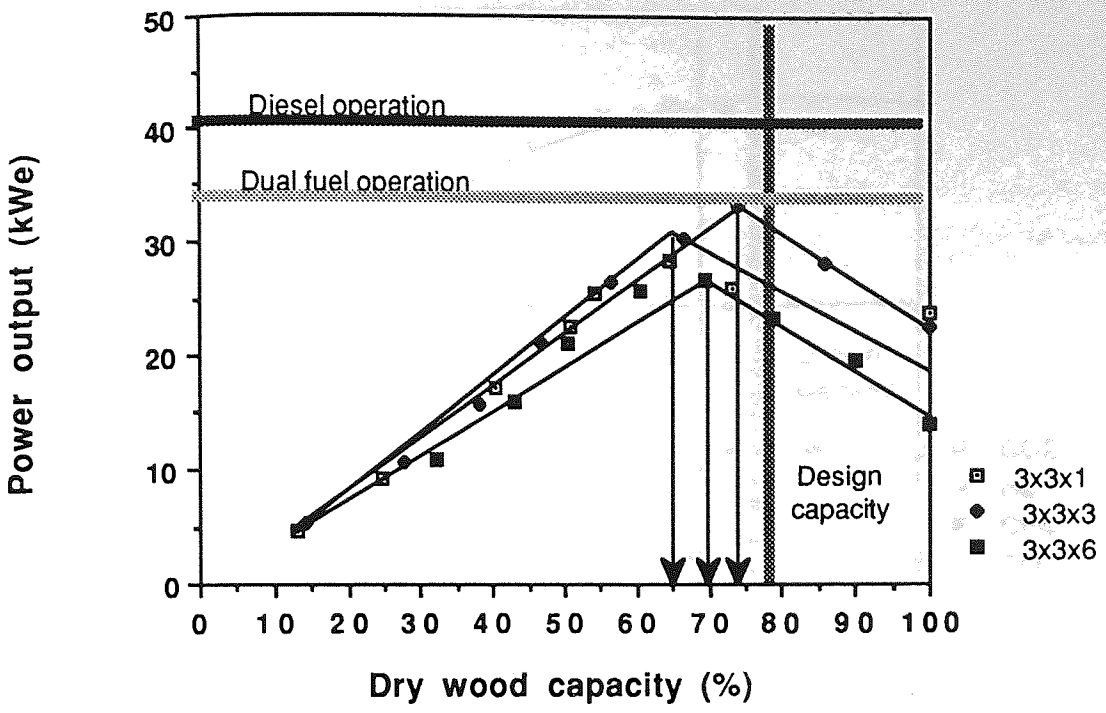


Figure 6.20 Influence of dry wood capacity on power output

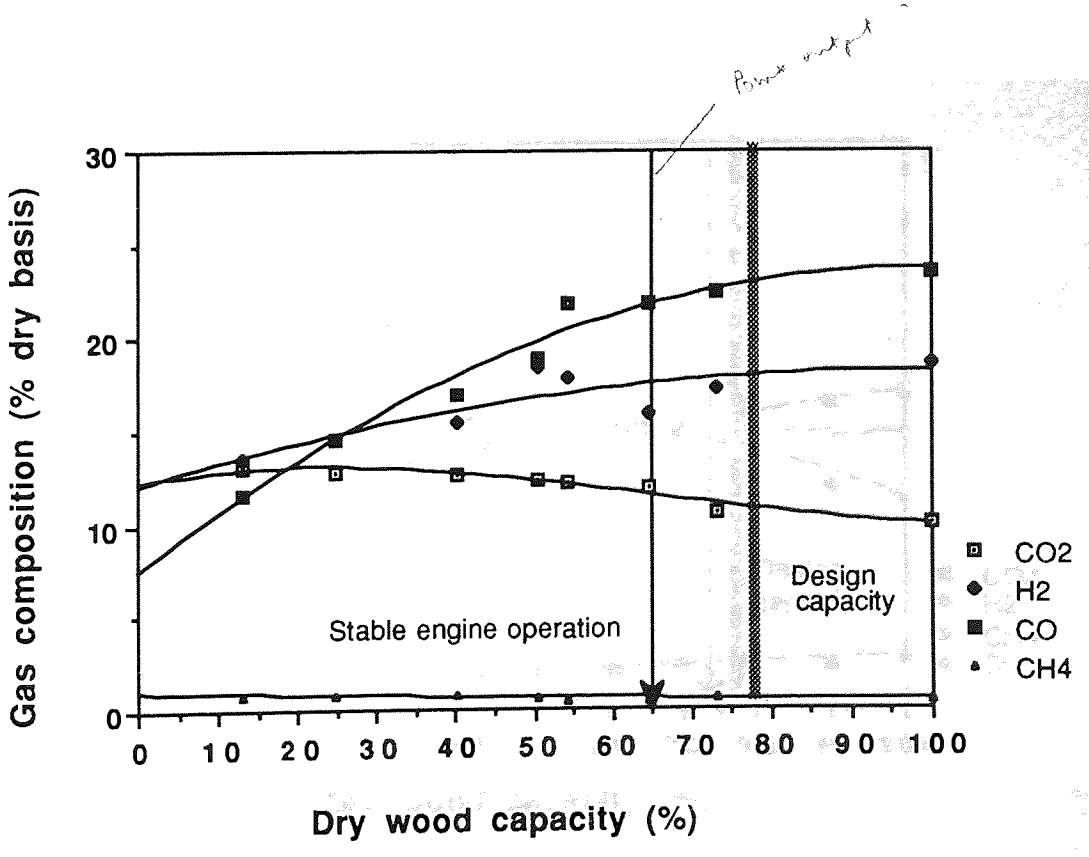


Figure 6.21 Influence of dry wood capacity on gas composition for wood of size 3cm x 3cm x 1cm

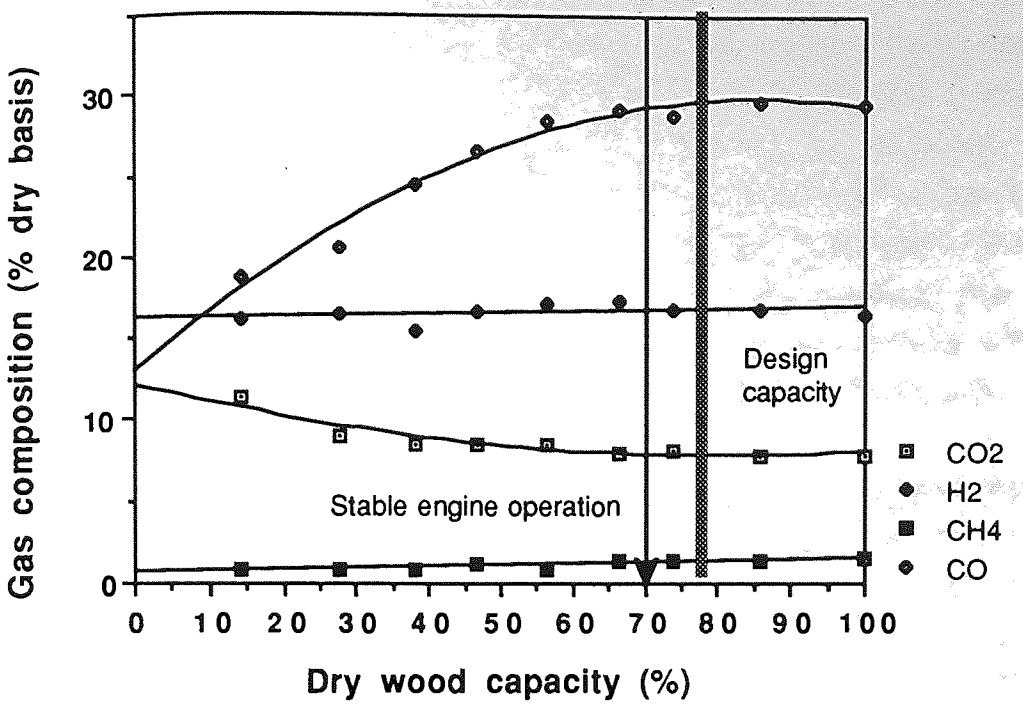


Figure 6.22 **Influence of dry wood capacity on gas composition for wood of size 3cm x 3cm x 3cm**

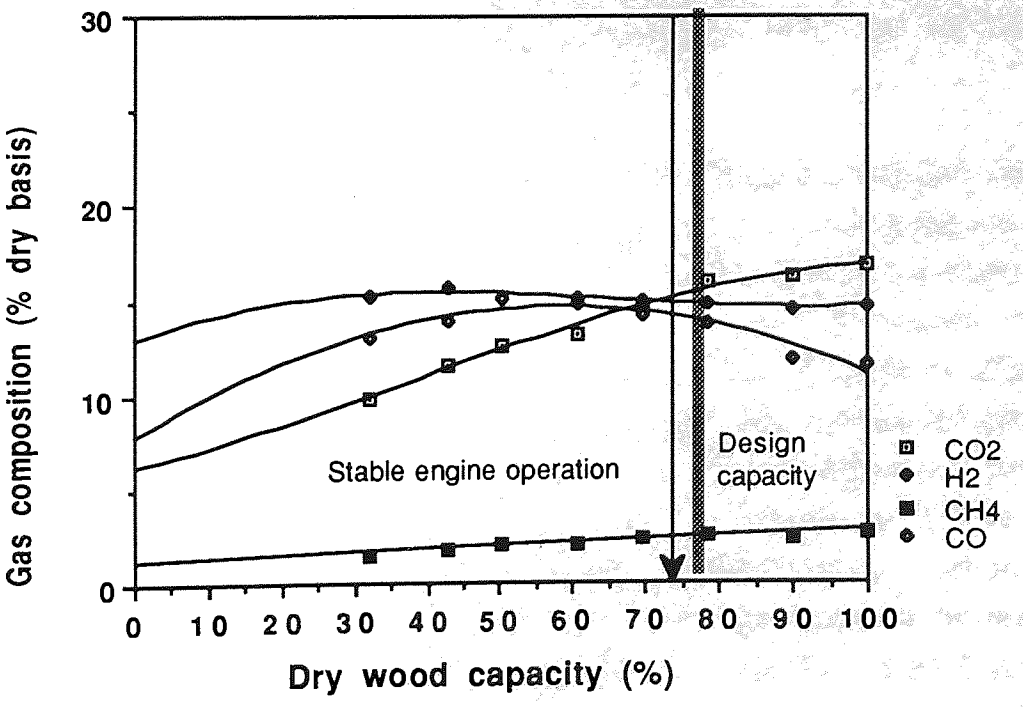


Figure 6.23 **Influence of dry wood capacity on gas composition for wood of size 3cm x 3cm x 6cm**

From Figure 6.18, it was found that up to the design capacity of the gasifier or about 78 % of the maximum capacity, the gas heating value increased with an increase in dry wood capacity for all three sizes of wood. The increase in the gas heating value with dry wood capacity is due to an increase in the useful heat fraction that favours the production of more combustible gases (see following paragraph). Consequently, the cold gasification efficiency and hence power output will also increase with an increase in the dry wood flow rate as illustrated in Figure 6.19 and 6.20.

The increase in the cold gas efficiency can also be explained by the hypothesis that above a certain dry wood capacity, the heat losses through the wall of the gasifier were relatively constant (see Figure 6.9). This means that beyond this capacity, the useful heat fraction for reduction will increase resulting in an increase in CO content. This is illustrated in Figure 6.21 and 6.22. However, for size 3 cm x 3 cm x 6 cm, the CO remained relatively constant over the same range of dry wood capacity. This could be due to a more dominant influence of bigger particle size on gas composition (see section 6.21.3). For the same reason, the proportion of hydrogen for wood size 3 cm x 3 cm x 1 cm and 3 cm x 3 cm x 6 cm also increased with wood capacity. However, for wood of size 3 cm x 3 cm x 3 cm, the composition of hydrogen content remained relatively constant for which no satisfactory explanation can be deduced.

The trials also indicated that beyond the design capacity the gas heating value remained constant (or even decreased for wood of size 3 cm x 3 cm x 6 cm) as wood capacity increases. The same behaviour is also evident from the cold gas efficiency as dry wood capacity increases. The maximum cold gas efficiency for wood of size 3 cm x 3 cm x 1 cm was found to be about 55 % of the maximum dry wood capacity. Similarly, the maximum cold gas efficiency for wood size 3 cm x 3 cm x 3 cm and 3 cm x 3cm x 6 cm was found to be 74 % and 79 % of the maximum dry wood capacity. It is believed that increased throughput will result in the disintegration of the reaction zone "bubble" with potential instability of the gasification process and the reaction zone. This "bubble" theory is explained in section 6.21.6.2. The disintegration of the bubble probably also resulted in a constant or even a decrease in the composition in the H_2 and CO at dry wood capacity illustrated in Figures 6.21, 6.22 and 6.23.

Above the design capacity (see above), the power output from the engine was found to decrease for all wood sizes. The maximum dry wood capacity for stable engine operation was found to be about 65 % of the maximum dry wood capacity for wood size 3 cm x 3 cm x 1 cm. Similarly, the maximum dry wood capacity for wood size 3 cm x 3 cm x 3 cm and 3 cm x 3 cm x 6 cm was found to be about 70 % and 74 %. These ranges of dry wood capacity are also indicated in Figure 6.21, 6.22 and 6.23.

The above phenomena may be due to the physical limitation in gas throughput of the engine causing instability in the reactor with the engine behaving more as a pump. Long term operation at these high throughputs and careful measurements and analysis are necessary to explain this phenomena. It is possible that wood throughputs recorded above the maximum are not consumed, but caused by the gasifier adapting to an unusual overload situation with the pyrolysis process being more dominant. Further evidence of engine overload or instability can be obtained from Figure 6.35 where the thermal efficiency of the engine decreased significantly at high wood capacity.

From Figure 6.20, it can be concluded that the working range of the engine in dual fuel mode is 5-33.5 kWe or about 83.8 % of its design capacity on 100 % diesel. A similar observation was also reported by Yoon et al. (1978) in his downdraft coal gasifier studies.

6.21.3 Influence of particle size on gasifier performance

6.21.3.1 Data selection

Since both the length and breath of all the wood chips is 3 cm, the variation in particle size is taken as the different thickness of the wood chips, that is a variation from 1 cm to 6 cm. For the analysis, three different dry wood capacities are chosen, namely a low capacity represented by 15-18 kg/h, a medium capacity represented by 30-33 kg/h and a high capacity represented by 43-46 kg/h. All the runs selected for analysis are wood with an average moisture content of 10 % wet basis. The data selected is summarised in Table 6.31.

Table 6.31
Influence of particle size on gasifier performance

Runs	Wood size cmxcmxcm	Dry wood feedrate kg/h	Cold gas efficiency %	Gas heating value MJ/Nm3	Power output kWe
Low capacity					
23	3 x 3 x 1	14.38	50.74	4.01	9.3
31	3 x 3 x 2	17.27	49.84	5.07	10.9
40	3 x 3 x 3	18.57	48.75	5.07	10.8
48	3 x 3 x 4	14.47	33.05	4.42	6.1
57	3 x 3 x 5	18.21	34.43	4.38	8.7
Medium capacity					
26	3 x 3 x 1	31.72	63.61	5.20	25.7
33	3 x 3 x 2	30.38	54.22	5.62	21.2
42	3 x 3 x 3	31.43	52.72	5.90	21.3
52	3 x 3 x 4	31.79	62.42	6.20	25.1
59	3 x 3 x 5	32.25	47.02	5.14	19.6
67	3 x 3 x 6	28.96	43.03	4.46	16.2
High capacity					
28	3 x 3 x 1	42.75	53.69	5.26	26.1
36	3 x 3 x 2	44.33	58.01	5.85	32.8
44	3 x 3 x 3	44.85	57.77	6.47	30.5
54	3 x 3 x 4	46.85	54.39	6.19	29.1
61	3 x 3 x 5	44.76	44.16	5.44	28.8
70	3 x 3 x 6	46.82	52.18	4.61	26.8

6.21.3.2 Data analysis

The results of the analysis are summarised in Figure 6.24, 6.25, 6.26, 6.27, 6.28 and 6.29.

The effect of particle size of wood can be analysed in terms of the surface area to volume ratio. It is desirable to offer a high fuel surface area in order to improve the gasification rate because the heat penetration time and area available for the solid-gas reactions are both dependant on particle geometry (Reed,1988).

The surface area to volume of wood used is summarised in Table 6.32.

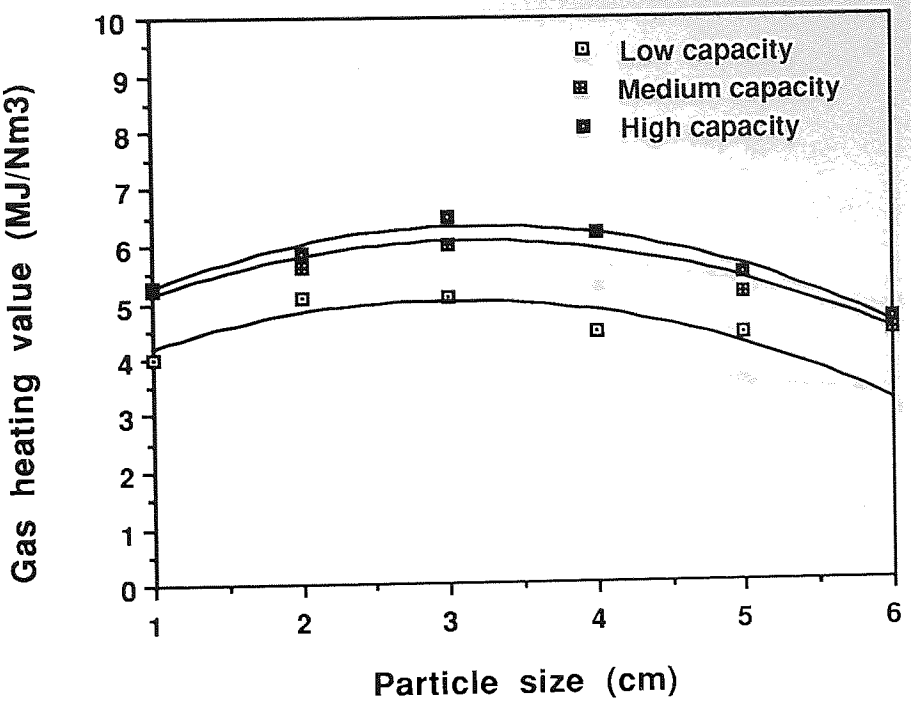


Figure 6.24 Influence of particle size on gas heating value

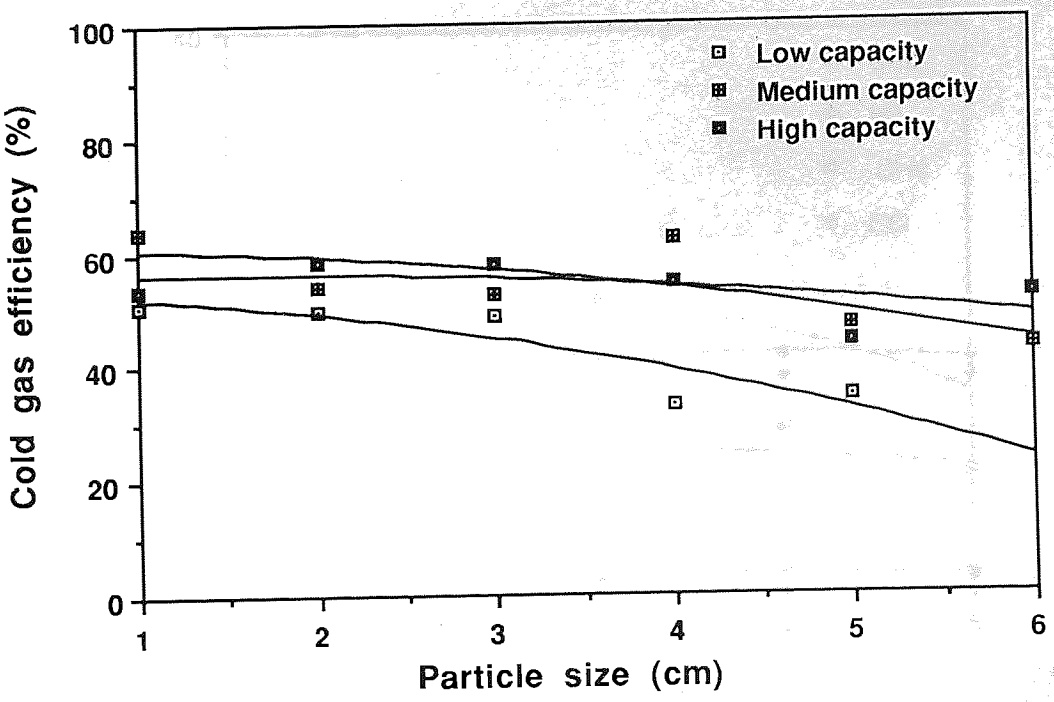


Figure 6.25 Influence of particle size on cold gas efficiency

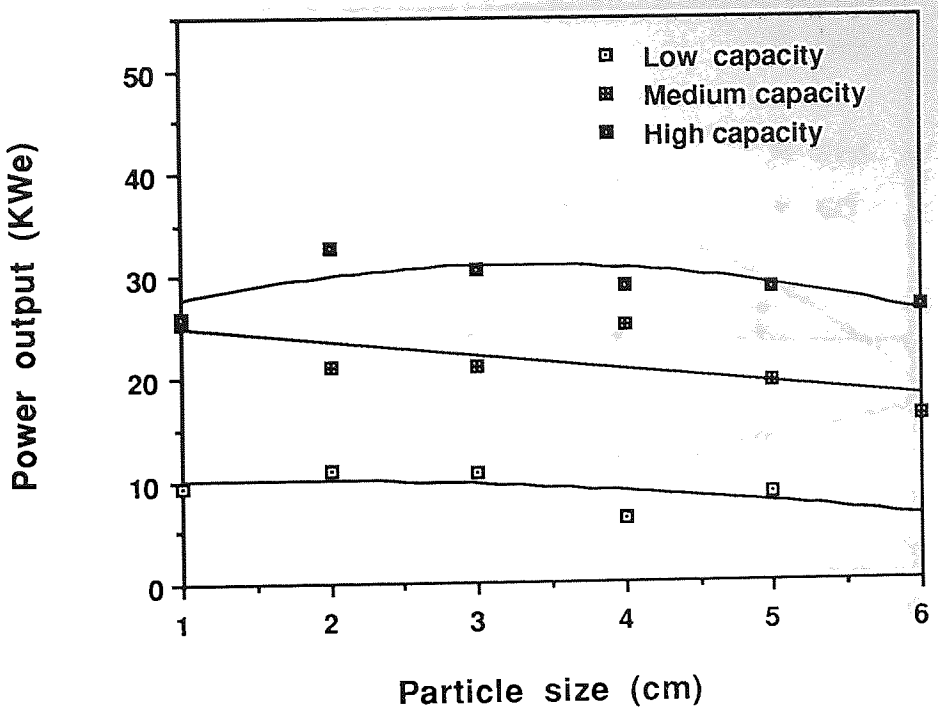


Figure 6.26 Influence of particle size on power output

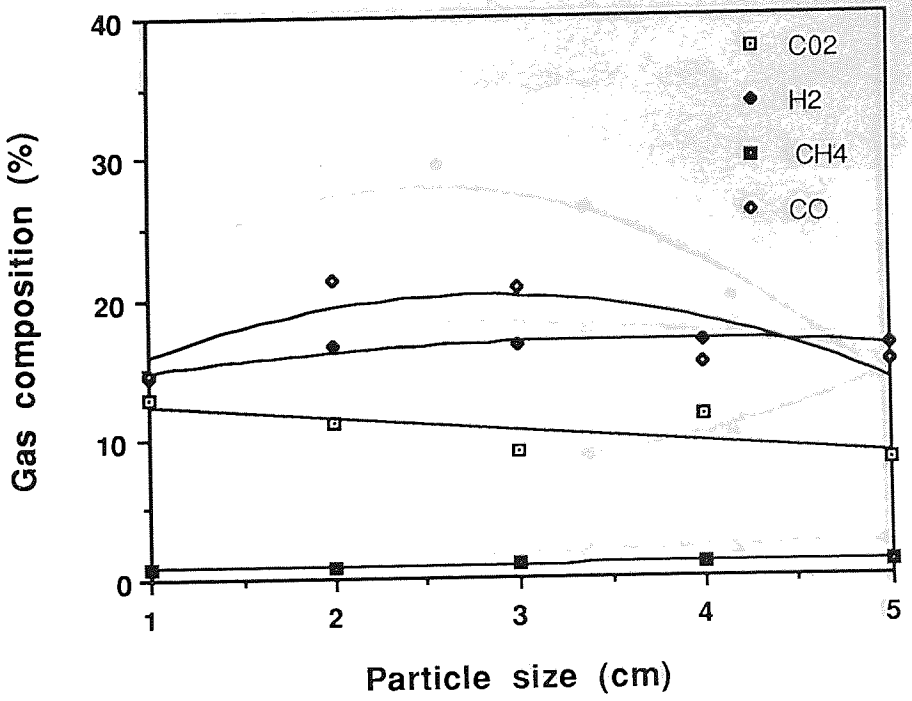


Figure 6.27 Influence of particle size on gas composition for low capacity

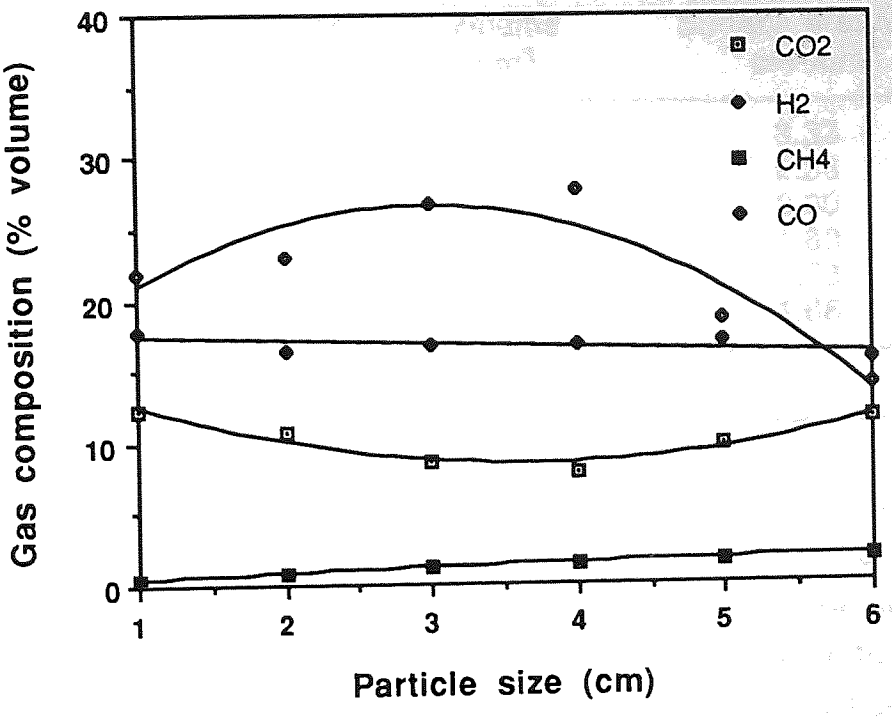


Figure 6.28 Influence of particle size on gas composition for medium capacity

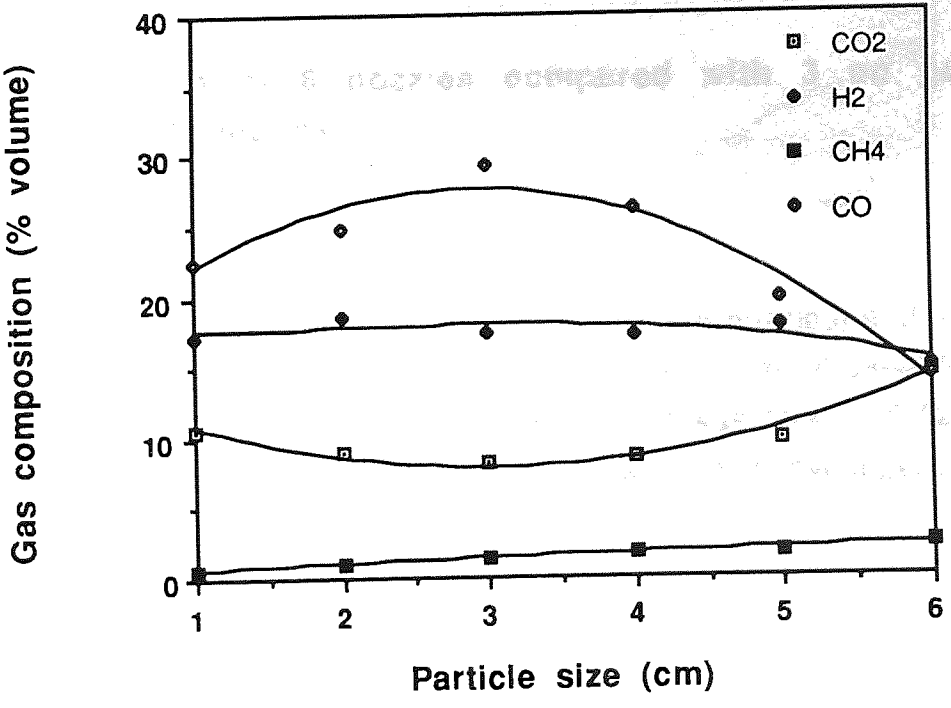


Figure 6.29 Influence of particle size on gas composition for high capacity

Table 6.32
Surface area to volume of wood of different sizes

Wood cmxcmxcm	Surface area* cm^2	Volume cm^3	Surface area/volume cm^2/cm^3
3 x 3 x 1	30	9	3.33
3 x 3 x 2	42	18	2.33
3 x 3 x 3	54	27	2.00
3 x 3 x 4	66	36	1.83
3 x 3 x 5	78	45	1.73
3 x 3 x 6	90	54	1.66

* Assuming that the wood are regularly shaped blocks

In terms of fuel surface area to volume ratio, wood sizes 3 cm x 3 cm x 1 cm are theoretically more favourable compared with 3 cm x 3 cm x 6 cm. This phenomenon is evident in Figure 6.25 and Figure 6.26 where the cold gas efficiency and power output of the gasifier decreases as particle size increases. However, Figure 6.24 indicates that uniform shaped particles gave better gas heating value than non uniform shaped particles. It is believed that uniformly shaped particles could improve fuel flow resulting in better solid-gas reaction. This is illustrated in Figure 6.27, 6.28 and 6.29, where the CO composition peaked for particle of size 3 cm x 3 cm x 3 cm.

6.21.4 Effect of 6 nozzles compared with 3 on gasifier performance

6.21.4.1 Data selection

Data for the analysis was selected from runs 74-79 (6 nozzles) and runs 80-85 (3 nozzles). The dry wood flow rate was varied from 14.33-48.97 kg/h while the average moisture content of wood used was 15.4-17.5 %. Only rubberwood of size 3 cm x 3 cm x 1 cm was used for this investigation. The data selected is summarised in Table 6.33.

Table 6.33
Influence of number of nozzles on gasifier performance

Runs	Nozzles number	Dry wood capacity kg/h	Dry wood capacity %	Tar content kg/h
74	6	12.90	27.87	1.46
75	6	14.33	30.96	1.48
76	6	32.04	69.23	4.20
77	6	34.37	74.27	4.32
78	6	46.28	100.00	5.19
79	6	45.18	97.62	5.26
80	3	14.08	28.75	0.88
81	3	12.83	26.20	0.93
83	3	35.65	72.80	1.04
84	3	45.09	92.08	1.66
84	3	48.97	100.00	1.67

6.21.4.2 Data analysis

The results of the analysis is summarised in Figure 6.30.

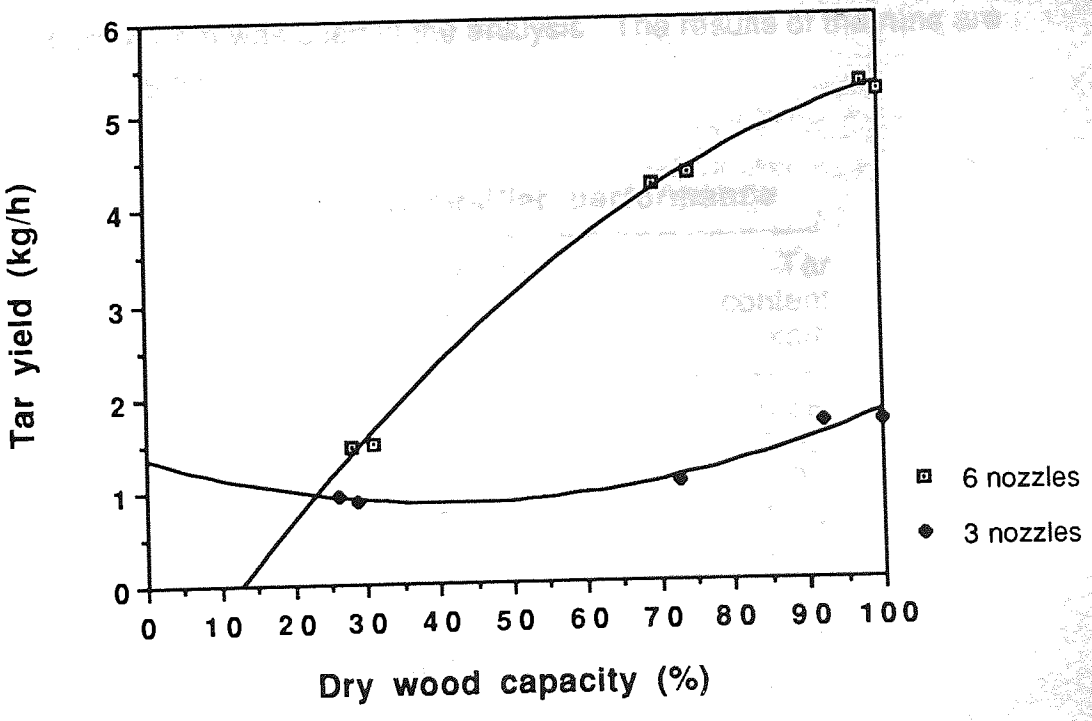


Figure 6.30 **Influence of dry wood capacity on tar yields for 3 and 6 air inlet nozzles**

It was believed that a more uniform air distribution from using 6 nozzles instead of 3 would result in a lower level of tars. However, from Figure 6.31, it is clear that the use of 6 nozzles appears to be disadvantageous in terms of tar cracking ability for dry wood capacities of above 30 %.

Since the cross-sectional area of each nozzle is the same, for the same volume of air going into the gasifier, a 6 nozzle configuration will provide air at a lower inlet velocity to the reaction zone compared to a 3 nozzle configuration. The greater reliance on air diffusion may cause areas in the reactor that are not reached by oxygen resulting in cold spots where tarry vapours can pass through uncracked. This hypothesis is, however, not compatible with the general reaction model proposed in section 6.21.6.

6.21.5 Influence of throat diameter on tar cracking

6.21.5.1 Data selection

Data for analysis was selected from runs 80-85 and from runs 96-101. The moisture contents for these runs were between 14.9-16.8 % (wet basis) while the dry wood flow rate was varied from 12.83 to 53.14 kg/h. Only fuel size 3 cm x 3 cm x 1 cm was used in the analysis. The results of the runs are tabulated in Table 6.34.

Table 6.34
Influence of throat diameter on gasifier performance

Runs	Throat diameter cm	Dry wood feedrate kg/h	Tar content kg/h
80	20.2	14.08	0.88
81	20.2	12.83	0.93
83	20.2	35.65	1.04
84	20.2	45.09	1.66
85	20.2	48.97	1.67
96	10	15.69	1.46
97	10	23.80	1.64
98	10	28.62	2.02
99	10	41.67	2.11
100	10	48.31	2.94
101	10	53.14	3.10

6.21.5.2 Data analysis

The result of the analysis is illustrated in Figure 6.31.

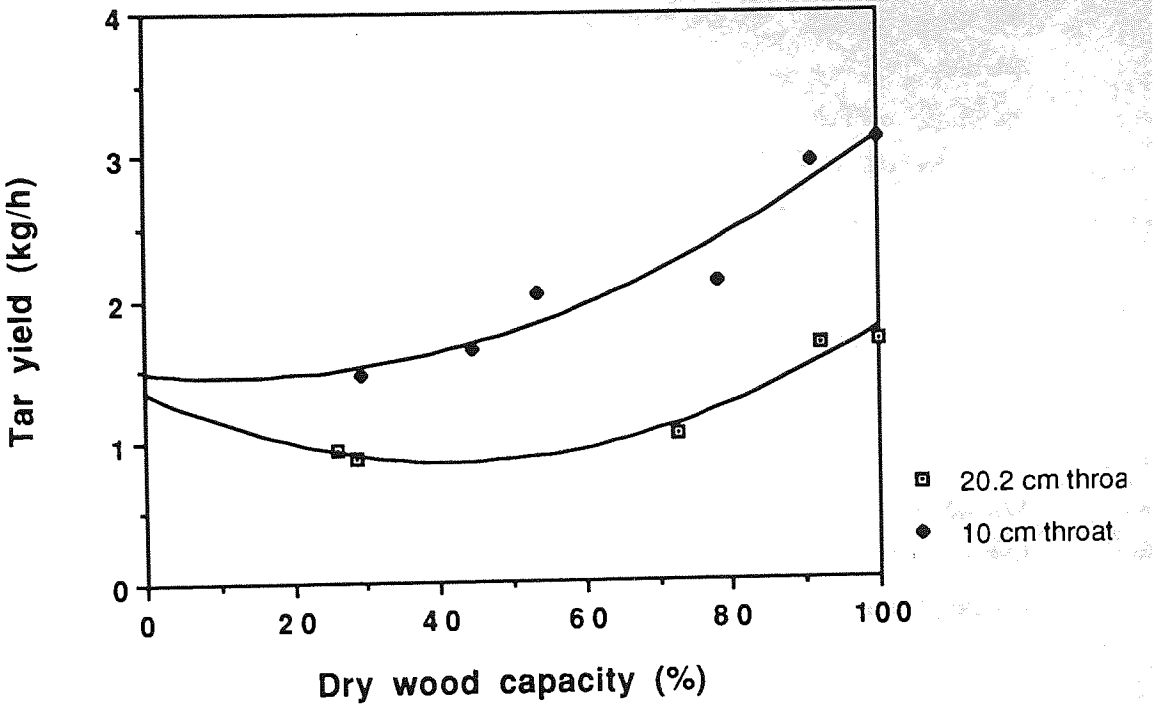


Figure 6.31 Influence of dry wood capacity on tar yield for 20.2 cm and 10.0 cm throat diameter

The smaller throat diameter was expected to create a hotter zone to improve tar cracking. Figure 6.31 shows that when the throat diameter was reduced from 20.2 cm to 10 cm there was no reduction in the tar condensed. The failure of better tar cracking for the 10 cm diameter throat may be due to the occurrence of bridging above the throat (which could be observed through the sight glass) which gave rise to the occurrence of voids allowing pyrolytic products to pass through uncracked. For low wood capacity, breaking the bridging by poking the feedstock through the sight glass is quite effective. However as the flow rates of wood increases, the bridge was more difficult to dismantle resulting in much higher tar formation at high wood capacity for the 10 cm throat as compared with the 20.2 cm throat.

6.21.6 Influence of turndown ratio on tar content of gas and methane composition

Turndown is defined as the ability of the gasifier to respond to changes in demand for product gas or wood throughput and at the same time be operated with a stable reaction zone (see section 4.9). The stable reaction zone is measured by the stable power output for a given dry wood capacity. Turndown can be expressed as turndown percentage and is defined as:

$$\frac{\text{Dry wood capacity}}{\text{Maximum dry wood capacity for stable operation}} * 100$$

Alternatively, it can also be expressed as a turndown ratio, namely:

$$\frac{\text{Maximum dry wood capacity for stable operation}}{\text{Dry wood capacity}}$$

Turndown is often quoted in gasifier trade leaflets, but most of these values are ambiguous because the basis from which turndown is determined is not specific. No published literature has been found to explain the phenomena of turndown.

There are a number of hypotheses that can account for turndown. Two possible hypotheses called the "bubble theory" are described here. It is believed that a feed particle in a gasifier moves progressively downwards through the reactor and that there will be no change until it approaches to within approximately one particle diameter of the reaction zone (Reed et al., 1985). The lowest part of the particle which is nearest to the top of the reaction zone then begins to pyrolyse. The time required for pyrolysis of the particle depends only on the rate of heat transfer to the surface. The heat is transferred primarily by radiation and convection from the oxidation of pyrolysis products. It can range from 30-100 seconds (Reed et al., 1985; Earp, 1988). The total pyrolysis process occurs within a height of not more than 2 particles in diameter.

On completion of pyrolysis, a flaming red particle of char drops to the surface of the char bed and disappears. The entire reaction zone from commencement of pyrolysis until gasification is believed to be not more than 3-5 particle diameters.

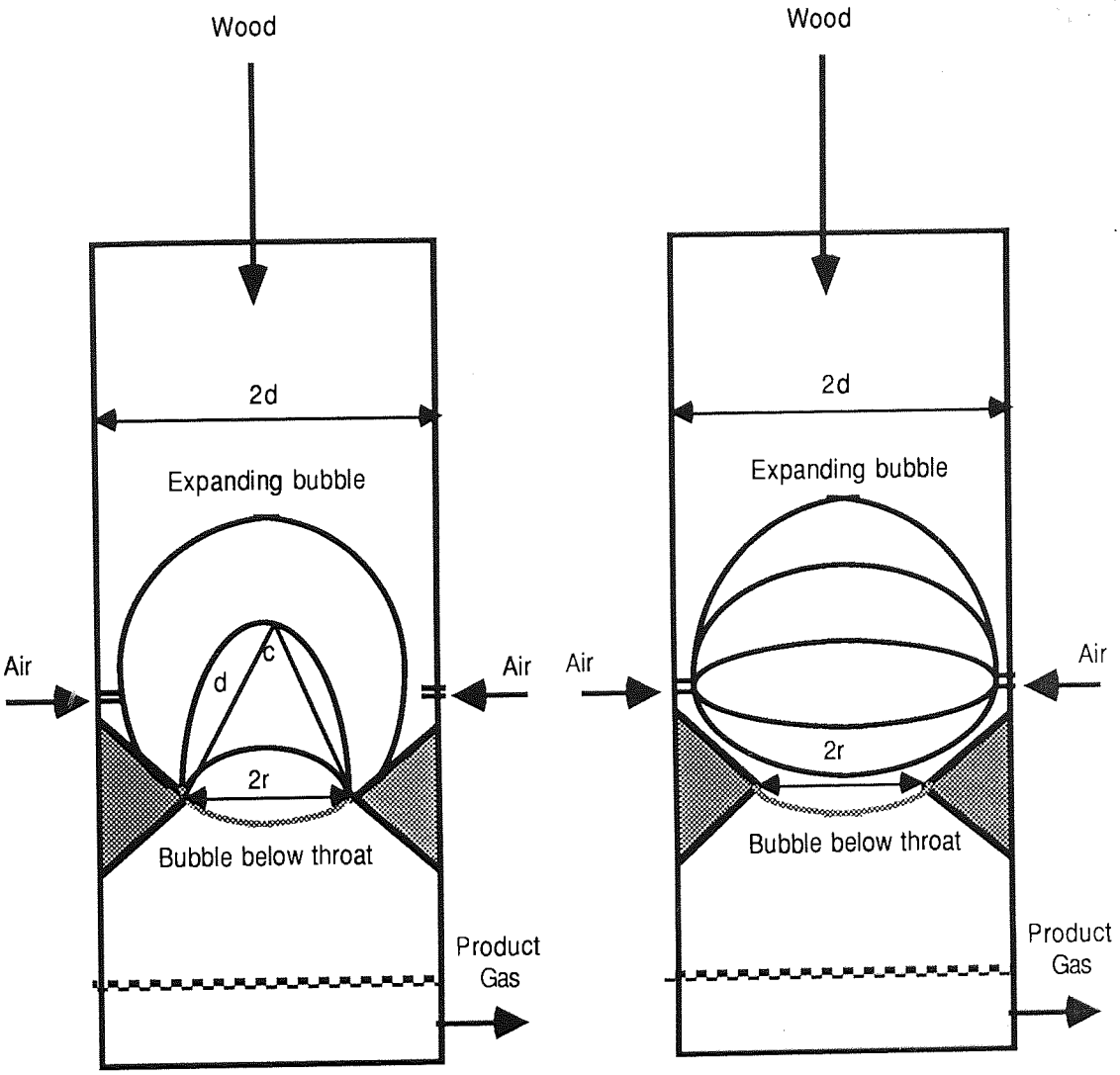


Figure 6.32 Bubble formation in reaction zone

The two possible hypothesis that can account for turndown are illustrated in Figure 6.32. The first hypothesis is an arched reaction zone above the throat and the second is a"bubble" around or between the air injector points.

Hypothesis 1 Arched reaction zone above the throat

In an arched zone hypothesis, it is believed that the reaction zone grows into a hemispherical shell around the throat. As gas demand increases due to higher wood capacity, the surface area of the hemispherical shell also increases.

The minimum level of operation which correspond to a minimum turndown percentage (TD_{min}) is proportional to the total cross sectional surface area

across the throat. Hence,

TD_{min} $= k * \pi * (r)^2$ where k= constant and r= throat radius

$= 102.01k\pi$, when r = 10.1 cm

An intermediate turndown is, for example proportional to half the surface area of a sphere. Hence,

$TD_{medium} = k * 4 * \pi * (10.1)^2/2 = 204.02\ k\pi$

The maximum level of operation which corresponds to a maximum turndown percentage is proportional to the total surface area of a sphere across the diameter (d) of the gasifier less the segment below the throat. For the gasifier used, the d = 2r, c = 60° and the maximum surface area above the throat is 5/6 the surface area of a sphere. Hence,

$TD_{max} = k * 4 * \pi * 5 * (22.5)^2/6 = 1687.5\ k\pi$

Thus, the minimum turndown percentage (or maximum turndown ratio) for the gasifier is:

$$= \frac{102.01}{1687.5} * 100 = 6.0\ \%$$ or a turndown ratio of 16.5

The main weakness of this hypothesis is that the likely mechanism of heat transfer to the particle for primary pyrolysis is mainly by radiation upwards from a hot char surface. The mechanism for heat transfer of particles within the reaction zone across the throat will not be effectively reacted as there is no radiation source at low capacity unless there is a hot grate or hearth below the throat.

Hypothesis 2 Bubble around or between the air injector port

In the second hypothesis, it is postulated that a spherical or ovoid "bubble" may be formed between the air injectors instead of across the throat. However, the behaviour of the "bubble" is similar to that of hypothesis 1. At higher capacities, the two theories merge. Thus the overall turndown ability of the reactor will be limited by largest diameter of the reactor bed and the smallest diameter of the throat or the minimum distance between the air injectors.

It would be therefore be expected that turndown of the gasifier will be highly dependant on wood properties such as shape, size, moisture content and

throughput. Variation of these parameters will cause the "bubble" to expand or contract in order to achieve stability in the reactor.

6.21.6.1 Data selection

Data for the analysis is taken from runs 22-73. Three representative sizes discussed in section 6.21.2 with an average moisture content of 10 % are chosen. The data for the analysis is summarised in Table 6.35.

Table 6.35
Influence of wood capacity on turndown ratio

Runs	Wood size cmxcmxcm	Turndown* %	Tar content g/Nm^{3**}	Methane %
22	3 x 3 x 1	20.22	17.80	0.8
23	3 x 3 x 1	38.07	28.93	0.8
24	3 x 3 x 1	62.25	17.56	0.7
25	3 x 3 x 1	78.36	14.68	0.6
26	3 x 3 x 1	83.98	16.76	0.4
27	3 x 3 x 1	100.00	16.38	0.5
28	3 x 3 x 1	113.22	33.33	0.6
29	3 x 3 x 1	154.77	45.08	0.5
39	3 x 3 x 3	19.01	60.83	0.8
40	3 x 3 x 3	37.34	54.33	0.9
41	3 x 3 x 3	51.53	47.05	0.9
42	3 x 3 x 3	63.21	42.09	1.2
43	3 x 3 x 3	76.41	40.20	0.9
44	3 x 3 x 3	90.20	43.58	1.4
45	3 x 3 x 3	100.00	34.74	1.3
46	3 x 3 x 3	116.12	37.35	1.3
47	3 x 3 x 3	135.59	46.05	1.3
66	3 x 3 x 6	46.05	44.49	1.4
67	3 x 3 x 6	61.85	39.24	1.8
68	3 x 3 x 6	72.58	41.32	2.1
69	3 x 3 x 6	87.21	37.02	2.1
70	3 x 3 x 6	100.00	35.21	2.3
71	3 x 3 x 6	113.55	33.83	2.5
72	3 x 3 x 6	129.66	36.16	2.4
73	3 x 3 x 6	144.18	45.74	2.6

* Expressed as turndown percentage
** Calculated by weight of condensed tar collected/ dry volumetric gas flow

6.21.6.2 Data analysis

The result of the analysis is illustrated in Figures 6.33 and 6.34.

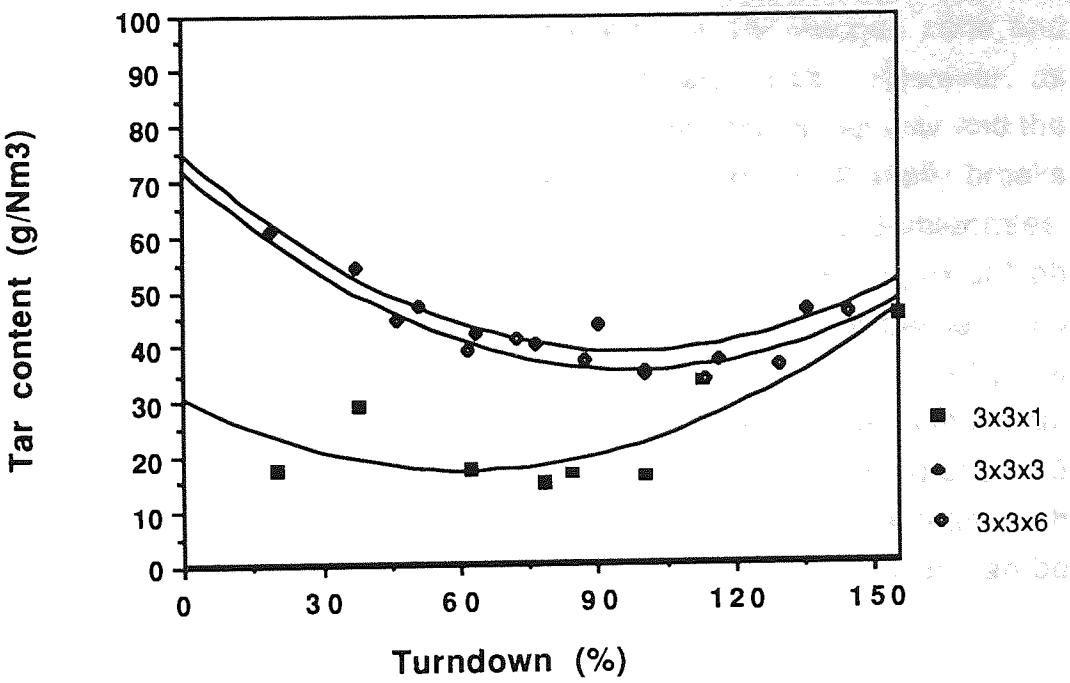


Figure 6.33 Influence of turndown on tar content of gas

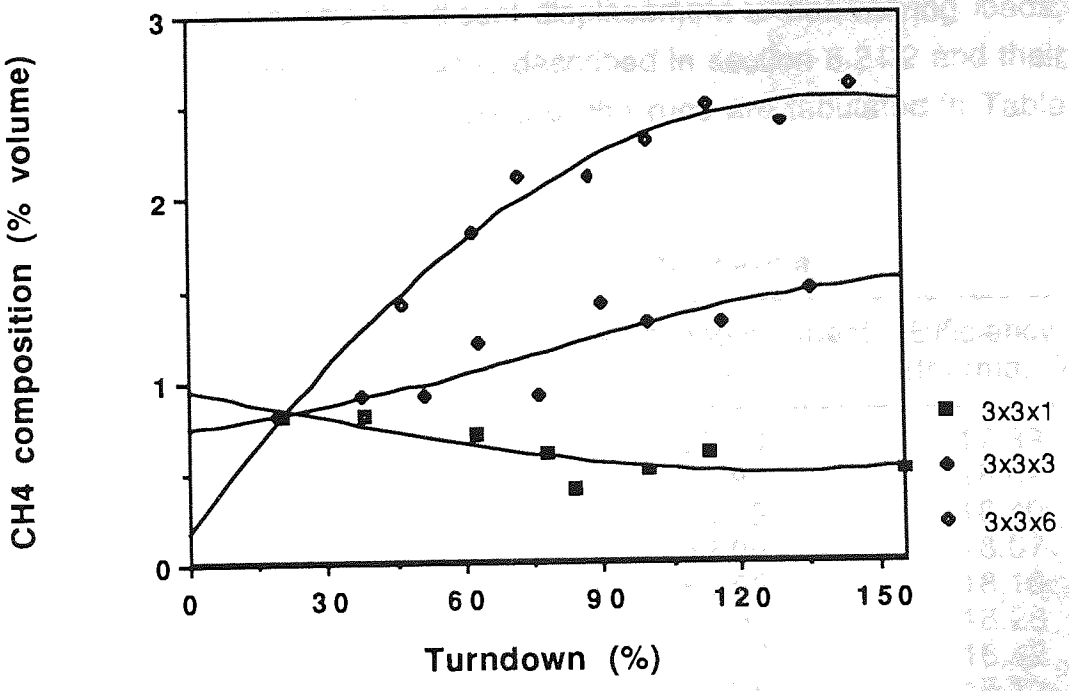


Figure 6.34 Influence of turndown on CH_4 composition

Figures 6.33 and 6.34 illustrate the effect of turndown on the tar content of the product gas and methane content. At low dry wood capacity or low turndown, the "bubble" is probably too small allowing for the existence of cold spots from which pyrolytic gas passes through uncracked. This accounts for a high tar content at low turndown. As turndown increases, the bubble stabilises resulting in better tar cracking in the reaction zone and hence a reduction in the tar content of the product gas. However, as turndown increases the gas production exceeds the system capacity and the "bubble" steadily grows in size and becomes unstable until it finally breaks up. At this stage, the tar cracking ability of the system also disintegrates. This is illustrated by the increase in the tar content of the product gas at high turndown for all the three wood sizes in Figure 6.33. Further evidence of the disintegration of the tar cracking ability of the system is illustrated by the increase in the composition of methane content for wood of size 3 cm x 3 cm x 1 cm and 3 cm x 3 cm x 3 cm as turndown increases. For wood of size 3 cm x 3 cm x 1 cm, the methane composition, on the contrary decrease with increasing turndown although the tar content increases. No reason can be found for why the methane composition decreases with turndown.

6.22 ENGINE PERFORMANCE

The performance of the engine on dual fuel is evaluated from the thermal efficiency of the engine and the diesel displacement under varying loads. For the analysis, the same three sizes described in section 6.21.2 and their respective runs were used. The results of the runs are tabulated in Table 6.36.

Table 6.36
Influence of wood capacity on engine performance

Runs	Wood size cmxcmxcm	Power output kWe	Diesel displacement %	Efficiency (thermal) %
22	3 x 3 x 1	4.6	67.10	17.39
23	3 x 3 x 1	9.3	67.91	18.02
24	3 x 3 x 1	17.4	68.59	18.40
25	3 x 3 x 1	22.8	69.09	18.07
26	3 x 3 x 1	25.7	69.52	18.16
27	3 x 3 x 1	28.5	70.05	18.28
28	3 x 3 x 1	26.1	69.92	16.42
29	3 x 3 x 1	23.8	69.25	15.12

Table 6.36 continued

39	3 x 3 x 3	5.3	65.24	18.01
40	3 x 3 x 3	10.8	65.79	16.97
41	3 x 3 x 3	15.9	66.57	18.13
42	3 x 3 x 3	21.3	67.65	18.16
43	3 x 3 x 3	26.5	70.59	18.64
44	3 x 3 x 3	30.5	68.98	17.04
45	3 x 3 x 3	33.5	68.85	15.58
46	3 x 3 x 3	28.2	68.18	12.70
47	3 x 3 x 3	22.7	67.64	12.23
66	3 x 3 x 6	11.0	67.38	17.36
67	3 x 3 x 6	16.2	67.91	18.23
68	3 x 3 x 6	21.3	68.45	18.33
69	3 x 3 x 6	25.8	69.25	17.80
70	3 x 3 x 6	26.8	69.52	15.98
71	3 x 3 x 6	23.3	69.25	12.69
72	3 x 3 x 6	19.8	68.71	11.45
73	3 x 3 x 6	14.2	68.18	7.78

6.22.1 Thermal efficiency of engine

The result of the analysis is illustrated in Figure 6.35.

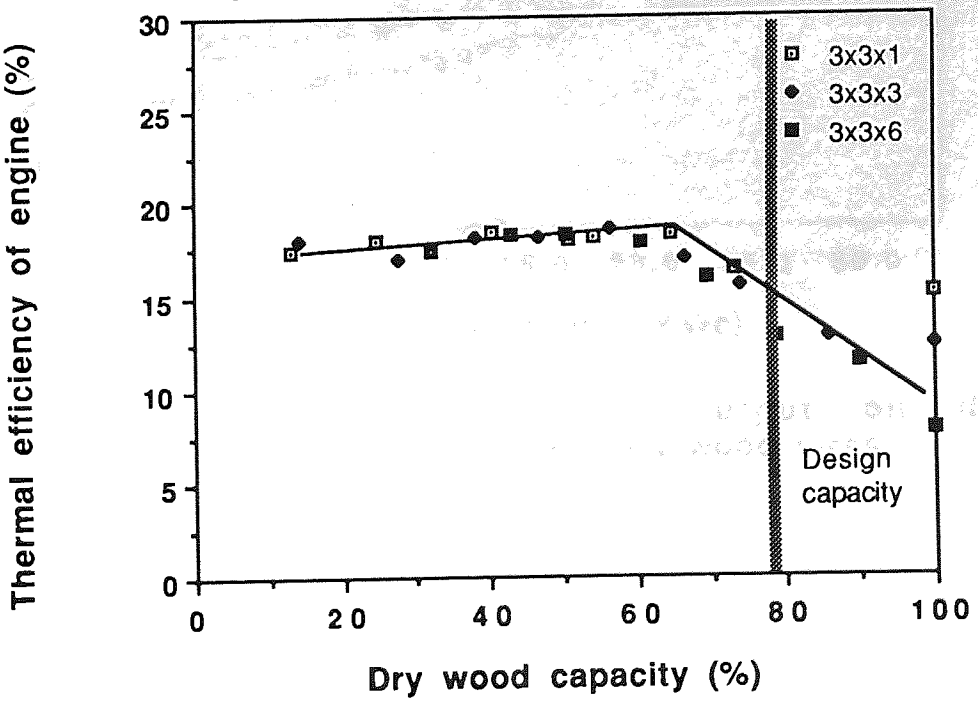


Figure 6.35 **Influence of dry wood capacity on thermal efficiency of engine for size 3x3x1, 3x3x3 and 3x3x6**

From Figure 6.35, shows that the thermal efficiency of the engine is constant at around 17-18 % up to a dry wood capacity of about 65 % for all the three wood sizes. As the dry wood capacity increases beyond 65 %, the thermal efficiency of the engine was observed to fall significantly for all the three wood sizes. It is believed that the drop in thermal efficiency of the engine at high dry wood capacity is due to the same reasons discussed in section 6.21.2.

6.22.2 Diesel displacement

The results of the analysis is illustrated in and Figure 6.36 and Figure 6.37.

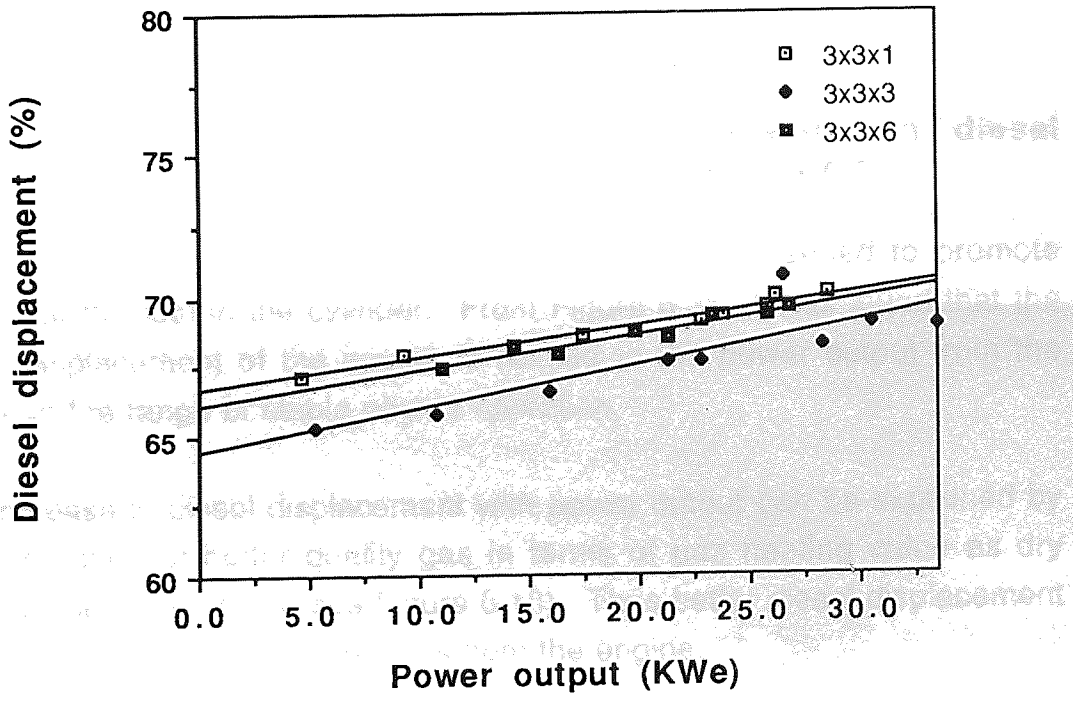


Figure 6.36 **Influence of power output on diesel displacement for different wood sizes**

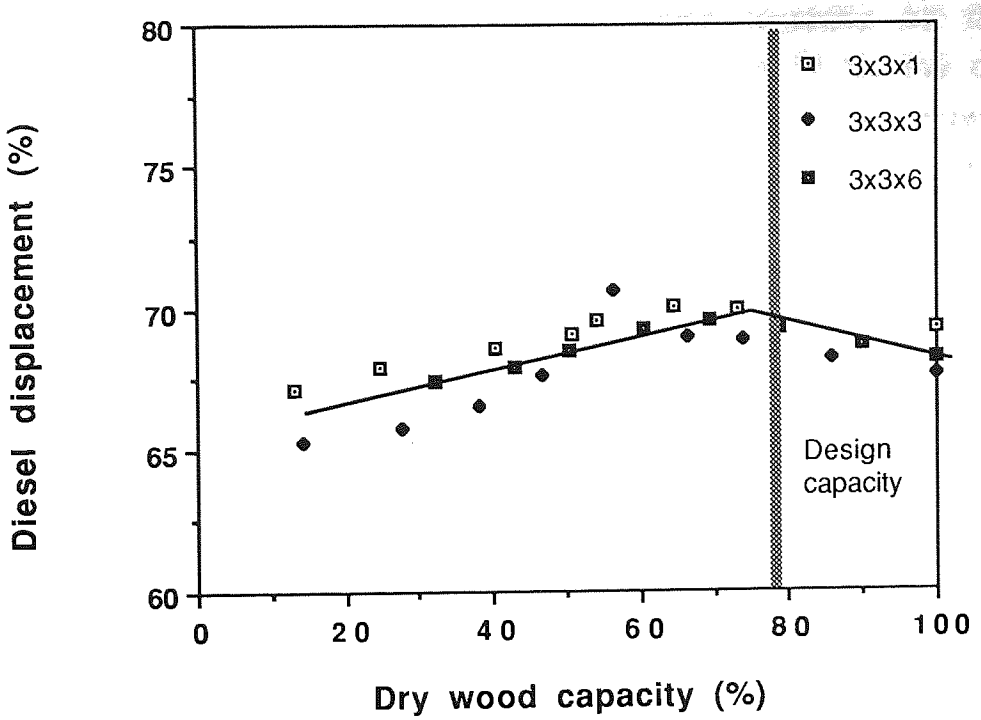


Figure 6.37 Influence of dry wood capacity on diesel displacement for different wood sizes

In dual fuel operation, a certain amount of diesel is needed to promote ignition of the fuel in the cylinder. From Figure 6.36, it was found that the diesel displacement of the engine is related to the power output from the engine in the range of stable engine operation.

The increase in diesel displacement with power output can be explained by the generation of better quality gas in terms of gas heating value as dry wood capacity increases (see Figure 6.18). Thus better diesel displacement is achieved at higher power outputs from the engine.

It was also found that wood of 3 cm x 3 cm x 1 cm gave better diesel displacement than wood of size 3 cm x 3 cm x 3 cm or 3 cm x 3 cm x 6 cm. However the diesel displacement of regularly shaped wood (3 cm x 3 cm x 3 cm) gave the lowest diesel displacement although it has the highest gas heating value as illustrated in Figure 6.18. It is not very clear as to why the diesel displacement is lower, but it is speculated that optimum air-product gas mixing may not have been achieved during the experiment. The maximum diesel displacement achieved in this research project was about 70 % for all the three wood sizes.

Figure 6.37 illustrates the influence of wood capacity on diesel displacement. Up to a dry wood capacity of about 70 %, the diesel displacement was found to improve with dry wood capacity. However, beyond this capacity, the diesel displacement was found to decrease due to the same reasons discussed in 6.21.2.

6.22.3 Exhaust gas analysis

The exhaust gas analysis measured by the engine Bosch Exhaust Gas Analyser (see chapter 5) for run 83 is summarised in Table 6.37.

Table 6.37
Exhaust gas analysis

Exhaust gas temperature (°C)	Gas type	% by volume
509.3	Carbon monoxide	2.70
509.3	Carbon dioxide	12.70
509.3	Hydrogen gas	2.20
509.3	Nitrogen gas	82.40

The analysis of the exhaust gas indicates that the product gas is almost completely burnt in the engine as the composition of H_2 and CO was found to be low. It implies that the engine is coping well with producer gas.

6.22.4 Engine wear

When the engine was overhauled after run 101 (about 550 hours), the valves, valve seats and piston crowns were examined very closely because these are the parts that are exposed to temperatures beyond the design capacity of the engine.

The engine was sent to Universiti Teknologi Malaysia for a physical evaluation. There were no signs of any abnormal engine wear on the valves, valve seats and guides. The internal bore diameters were found to be all within the original manufacturing tolerances.

However, it was apparent that the top piston ring groove was suffering from accelerated wear compared to a similar engine operating on diesel fuel

only. It is speculated that this accelerated wear may be attributed to the "dryness" in the piston ring area due to the lack of lubricative qualities of producer gas compared with diesel fuel. This wear would be further accelerated by the presence of particulates in the product gas.

A visual examination of the nozzles indicated that there was no abnormal erosion of the injector nozzle tip. However, the effect of producer gas on the nozzle life-span could not be established due to the limited running hours on the engine.

It was found that part of the oil channels were blocked probably due to dirt and dust from the surrounding getting into the oil during the filling up process. The presence of oil and dirt probably affected the efficiency of the oil pump in the engine.

The top of the pistons were covered with deposits of carbon. This deposit could be one of the reasons for the occasional explosions or detonations at the exhaust pipe of the engine during the operation of the gasifier.

Although there were a few problems associated with the engine for runs 63, 64 and 65 (see section 6.12), there were generally no major problems in operating the engine throughout the research.

In order to be able to get more information on the performance of diesel engine on dual fuel, oil samples (from the engine oil storage tank) were taken at approximately every 100 hours for analysis at Universiti Teknologi Malaysia. The results of the analysis are summarised in Tables 6.38 and 6.39. It was found that there was a decrease in the viscosity of engine oil and a significant increase in the level of trace metals compared with engine working on normal diesel fuel. This indicated a higher degree of engine wear possibly reducing engine lifespan in extended use (UTM, 1988).

Table 6.38
Engine oil analysis

sample No.	Engine hours	viscosity (100°C)
1	98	13.5 P
2	201	9.2 P
3	285	9.0 P
4	402	9.0 P

* Viscocity for normal SAE 30 at 100 °C = 25 P (UTM 1989)

Table 6.39
Trace metal analysis

Sample number (as above)	1	2	3	4
Trace metals analysis (ppm)*	290	376	599	733

* Trace metals normally consists of Si,Fe,Sn,Pb,Cu,Cr and Ni (Hollingdale et al., 1988)

Maximum trace metal composition for SAE oil is 280 ppm (UTM, 1989). However, the exact breakdown of the identity of the trace elements were not analysed during the research.

6.23 OPERATIONAL PROBLEMS

The following problems were encountered during the entire operation of the gasifier.

6.23.1 Feeding mechanism

Occasionally, small pieces of wood chips get trapped in the gate valve of the hopper preventing complete closure. If the wood chips are not removed, the gasifier cannot be sealed properly. Although this problem could be solved by manually removing the wood chips, the operation was found to be dangerous due to the flammability of the product gas.

6.23.2 Tar problem

During start-up large amounts of tar were deposited on the blower fan

blades when the motor of the fan was used for start-up. The condensed tar affected the performance of the fan because the movable parts of the fan have very close tolerance between the fanwheel and the fan casing. Cleaning of the fan had to be carried out quite frequently otherwise the fan motor would have burnt out. In the experimental programme, two fans had to be replaced.

6.23.3 Dual fuel feeding of engine

Since no changes had been made to the diesel fuel injection pump and other feeding mechanisms of the engine, immediate switch over could be easily made from dual fuel feeding to 100 % diesel fuel or vice versa. The system worked well but it was not optimum and in practice gave a fluctuation of between 40-60 Hz in the frequency. This will affect the variability of the wattmeter reading by ± 10 %.

6.23.4 Crack in refractory

Cracks and some erosion due to thermal stress in the refractory throat was observed after about 300 hours of operation during the cleaning up of the gasifier. Although there was no difficulty in sealing the cracks, the whole operation took about 2 days. This would cause a considerable loss in down time if the gasifier were used for long periods.

6.23.5 Erosion of the air injector nozzles

The parts of the air injector nozzles which were subjected to intense heat in the oxidation zone were found to have eroded and had to be replaced after 500 hours of operation. A possible solution to this problem may be to have a cast iron sleeve around the tip of the nozzles. When the nozzles are eroded, they can be replaced.

6.23.6 Sealing

The access doors of the ash chamber were difficult to seal because of their large surface area and because the sealing material was asbestos cord which hardened and become brittle at high temperature. Frequent air leaks

were believed to occur from this source.

6.23.7 Cleaning of the cooler

During cooling of the gasifier, tars from the product gas condensed inside the vertical pipes of the air-cooled condenser making them difficult to clean. If the tar deposits in the vertical pipes are not removed regularly they will affect the flow of the product gas and the efficiency of cooling. Bigger diameter vertical pipes would be preferable in future designs as it would be more accessible for cleaning.

6.23.8 Connecting flanges

The connecting flanges between pipes were made from mild steel plates. During the research, occasional of air leakage is believed to have occurred through the flanges. Although the leak could be reduced by tightening the bolts, it was occasionally difficult to carry it out during the gas operation because of concern over toxic gas leaking.

6.24 HAZARDS AND ENVIRONMENTAL EFFECTS

The quantity of tar and condensate yields from the gasifier was found to be 0.35-5.97 kg/h and 0.90-8.90 kg/h respectively. For large scale application of gasification in Malaysia the disposal of high quantities of tars and condensate would pose a major problem. So far the Department of Environment of Malaysia have only recommended incineration as the best way of disposal (Department of Environment of Malaysia, 1987; 1988). However, the incineration process may be an expensive process and more practical solutions have to be found.

The risk of carbon monoxide poisoning constitutes the main problem of producer gas operation. Exposure to high concentrations of carbon monoxide is very well documented in medical journals. The experience from extensive use of gasifiers in Sweden during the Second World War had found that exposure to even low concentration of producer gas can result in various symptoms such as headaches and irregular heart beat (Anon, 1979). However, the long term effects of low levels of carbon

monoxide poisoning has never been reviewed or studied. Nevertheless, the potential health risk of carbon monoxide exposure will be a serious problem if producer gas is introduced on a large scale in Malaysia, particularly if strict safety regulations and education of the operator are not emphasized.

CHAPTER 7

TECHNO-ECONOMIC EVALUATION OF RUBBERWOOD GASIFICATION IN MALAYSIA

7.1 INTRODUCTION

Foley and Barnard, (1983), in the presentation of biomass gasification in developing countries, cited the initial cost of the gasifier as the single most important factor determining the final cost. Variations in the reported cost of gasification equipment are very wide and may vary by a factor of 10 between that of a cheap locally fabricated unit and a sophisticated imported model. The systems currently produced in Europe and in the United States cost between MR$1200-3000/kW for the gasifier and the gas cleaning system alone. On the other hand systems available in Brazil can cost as little as MR$150-300/kW (Bridgwater et al., 1986; Bridgwater et al., 1987; Bridgwater, 1987; Gemcor, 1982; Vasconcelos and Furtado, 1987).

The traditional method of economic evaluation will require the capital cost, operating cost and the product selling price to be estimated. From this information, the payback time, return of investment and the net present value can be calculated (Allen, 1980; Peter and Timmerhaus, 1980). However, in the techno-economic evaluation of rubberwood gasification, it is difficult to estimate the value of the product and hence the production cost per kilowatt is used to evaluate the viability of the process.

The economics of rubberwood gasification depends on a number of factors such as the operating period, the system lifetime, load factor, diesel fuel cost, wood fuel cost, labour, maintenance and lubricant cost. The effects of this factors will be investigated in this chapter.

7.2 COST APPRAISAL METHODOLOGY

The two forms of cost to be considered is the capital cost and the operating cost. The capital cost is related to the cost of the equipment and the site related costs. The former is determined by the nature of the biomass and the character of the energy demand while the latter is related to the cost of site preparation, building, installation, commissioning , freight charges plus

insurance and related duties. Many reports have overlooked or seriously underestimated in the initial stages of small scale power supply projects.

Stassen and Stiles, (1987) suggested the use of the annualised investment cost as an effective method to arrive at an equally distributed annual cost for the items concerned. The annuity cost per year or ACC can be calculated by the use of the following formula:

$$ACC = \frac{C}{1-(1+i)^{-n}} * i \qquad [7.1]$$

where, ACC = annuity charge (cost/year)
C = Capital cost
i = Rate of interest
n = System lifetime.

7.3 ECONOMIC EVALUATION

In order to study the economics of gasification in Malaysia, both the capital cost and the operating cost must be estimated and assumed. The assumptions made are listed as follows:

7.3.1 Capital cost

For the purpose of this thesis, the capital costs of the gasifier will only represent the cost incurred to fabricate and install the gasifier and engine system at the Forest Research Institute of Malaysia. The cost of the diesel gen-set of a similar capacity is based on a locally assembled diesel engine (Kam, 1988). In both cases it does not include cost of buildings and site preparation for the systems.

The capital cost of fabricating the gasifier = MR$10312.50
The capital cost of the diesel engine gen-set = MR$13750.00

By taking the current interest rate in Malaysia as 10 % and a system life-span of 10 years (see section 7.3.2.1), the ACC from equation [7.1] for the gasifier is:

$$\frac{10312.50}{1-(1+0.10)^{-10}} * 0.10 = MR\$1678.3/y$$

Similarly, the ACC for the diesel engine = MR$1807.8/y

7.3.2 Operating cost

7.3.2.1 Annual operating hours,load factor and system lifetime

For the purpose of computing the annuity charge, it is assumed that both the gasifier and diesel gen-set are operating at 3000 hr/y or an average of ten hours per day. The load factor, which is defined as the percentage of the total maximum output load of the unit. For small capacity system like the unit used in the research, it is normally operated at a load factor (which is the percentage of full load) 80 % for both the gasifier and diesel gen-set (Stassen, 1989). Hence for an output load of 35 kWe, the total system working time is:

$$3000 * 0.80 * 35 = 84000 \text{ kWh/y}$$

The average life-span of the gasifier and diesel engine are assumed to be 10 years and 15 years respectively (Graf,1987; 1989).

7.3.2.2 Diesel cost

The current diesel cost is estimated at MR$0.80/l. For the estimation of the total diesel cost, data from run 25 is used. The data used are as follows (see section 6.18.1):

Specific diesel consumption on diesel gen-set = 0.374 l/kWh
Specific diesel consumption on dual fuel = 0.116 l/kWh
Total diesel consumed on diesel gen-set per year = 0.374 * 84000
= 31416 l
Total diesel consumed on dual fuel per year = 0.116 * 84000
= 9744 l
The total diesel cost required by the diesel gen-set = 31416 * 0.80
= MR$25135.8
Similarly, the total cost required by gasifier = MR$7795.2

7.3.2.3 Wood cost

The wood used for the gasifier is assumed to be rubberwood residues which are likely to be available in sufficient quantity. The cost of rubberwood residues is estimated to be MR$40/t within a delivery radius of 30 km (Gan, 1990). These figures are applicable to wet rubberwood with a moisture content of 10-15 %, (wet basis). The relevant data for the calculation of wood cost for run 25 are as follows:

From Appendix III,	wet wood feedrate	= 33.50 kg/h
From Appendix III,	power output	= 22.8 kWe
	Specific wood consumption	= 33.50/22.8 kg/kWh
		= 1.47 kg/kWh
	Total wood consumed per year	= 1.47 * 84000
		= 123480 kg

By taking the wood cost to be MR$40/t, then the total wood cost per year to run the gasifier is:

123480 * 40/1000 = MR$4939.2/y

7.3.2.4 Labour cost

The total cost of one operator to supervise and operate a diesel gen-set is estimated to be MR$1800/y. For operating the gasifier system, two operators will be needed because of additional duties of preparing wood and closer supervision of the gasifier compared with a diesel gen-set which will require only one worker. Thus the labour cost to run the gasifier and diesel engine is MR$3600/y and MR$1800/y.

7.3.2.5 Maintenance cost and lubricant cost

The cost of maintenance, and lubricant cost for this research were not monitored. The equivalent maintenance cost in Malaysia has to be estimated from the World Bank Monitoring Report (World Bank, 1988). The estimated costs are as follows:

For a gasifier system,	Maintenance cost	= MR$0.0125/kWh
	Lubricant cost	= MR$0.006/kWh
For a diesel gen-set system,	Maintenance cost	= MR$0.00625/kWh
	Lubricant cost	= MR$0.004/kWh

According to the World Bank Report, (1988), engines running on producer gas will require more maintenance care and lubrication oil changes due to the presence of contaminants in the gas.

The total maintenance cost per year for the gasifier is:

84000 * 0.0125 = MR$1050/y

The cost of lubricant in Malaysia is MR$2.50/l. Thus the total cost of lubricant per year for the gasifier is:

84000 * 0.006 *2.50 = MR$1260/y

Using similar procedure, the total maintenance and lubricant cost of the diesel gen-set is MR$525/y and MR$840/y.

All the data from the above calculations are summarised in Table 7.1 to be taken as the baseline case for the sensitivity analysis.

Table 7.1
Results of economic analysis for power generation

Cost components, MR$	Gasifier	Diesel
Annualised capital cost*	1678.3	1807.8
Annual operating cost		
fuel-diesel	7795.2	25132.8
wood	4939.2	
labour	3600	1800
maintenance	1050	525
lubricants	1260	840
Total annual production cost	20322.7	30105.6

* ACC (see section 7.2)

7.3.3 Production cost per kilowatthour

From Table 7.1, the total annual cost production cost for the gasifier and diesel engine system is MR$20322.7/y and MR$30105.6/y respectively.

Hence the production cost per kilowatt hour electricity production for the gasifier is:

20322.7/84000 = MR$0.242/kWh

For a diesel system, the energy cost per kilowatt is:

30105.6/84000 = MR$0.358/kWh

7.3.4 Sensitivity analysis.

In order to test the influence of variations in the baseline assumptions on the specific power costs, a sensitivity analysis was performed. Table 7.2 presents an outline of assumed variations in the different parameters. Only one parameter was varied at a time while the other factors were kept equal to the baseline assumptions.

Table 7.2
Variation of baseline assumptions.

	Baseline assumptions	Variation
1. Equipment cost	Not varied	Not varied
2. Interest rate	10 %	5 %
		10 %
3. Annual operating period	3000 hr	2000 hr
		4000 hr
4. System lifetime		
(gasifier)	10 y	8 y
		12 y
(diesel engine)	15 y	12 y
		18 y
5. Load factor	80 %	70 %
		90 %
6. Fuel cost	MR$0.80/l	MR$60/l
		MR$1.00/l
7. Wood cost	MR$40/t	MR$30/t
		MR$50/t
8. Manpower	MR$1800/y	MR$1600/y
		MR$2000/y
9. Maintenance		
Gasifier	MR$0.0125/kWh	MR$0.0120/kWh
		MR$0.013/kWh
Diesel engine	MR$0.00625/kWh	MR$0.0060/kWh
		MR$0.00650/kWh
10. Lubricant	MR$2.50/l	MR$2.00/l
		$3.00/l

7.3.5 Results of the sensitivity analysis

Table 7.3 presents a summary of the results of the calculations based on the baseline assumptions. To enable the results to be compared on a common basis, the percentage difference between the production cost of the gasifier and diesel system is first computed. The deviation of the percentage difference from the baseline value is then calculated as an arbitrary index to be used for comparison. An example is given as follows:
For variation in interest rate of 5 %, percentage difference is calculated as:

$$\frac{0.353-0.238}{0.238} * 100 \quad = 48.3\ \%$$

Similarly, the percentage difference for 10 % and 15 % can be calculated. The index for comparison is calculated by the following method:

Baseline value = 47.9 %

Index for 5 % variation = 48.3 % - 47.9 % = 0.4

The rest of the values in Table 7.3 is calculated by the same method. From Table 7.3, the main factors that will influence the production cost are:

a) annual operating period
b) diesel and wood cost
c) load factor
d) manpower cost

The second order factors are the annual interest rate, system lifetime, maintenance and lubricants cost.

An investigation into the effects of diesel, wood and operating period on production cost per kilowatthour is illustrated in Figure 7.1, 7.2 and 7.3

Assuming that other baseline assumptions are unchanged, Figure 7.1 illustrates that the cost of production of electricity for the gasifier system is cheaper than diesel system for diesel prices above MR$35/l. This figure assumes that all remaining factors used in the baseline assumptions remained unchanged.

Table 7.3
Results of sensitivity analysis, MR$/kWh

Parameters	Variation	Gasifier	Diesel	%	Index
Interest rate	5 %	0.238	0.353	48.3	+0.4
	10 % (B*)	0.242	0.358	47.9	0.0
	15 %	0.246	0.365	48.4	+0.5
Annual operating period	2000 h	0 273	0.380	39.2	-8.7
	3000 h (B)	0 242	0.358	47.9	0.0
	4000 h	0.226	0.348	54.0	+6.1
System lifetime (Gasifier)	8y	0.245	0.361**	47.3	-0.6
	10 y(B)	0.242	0.358	47.9	0.0
	12 y	0.240	0.357	48.8	+0.9
Load factor	70 %	0.251	0.365	45.4	-2.5
	80 % (B)	0.242	0.358	47.9	0.0
	90 %	0.235	0.354	48.8	+2.7
Diesel fuel cost	MR$0.60/l	0.219	0.284	29.7	-18.2
	MR$0.80/l (B)	0.242	0.358	47.9	0.0
	MR$1.00/l	0.265	0.433	63.4	+15.5
Wood cost	MR$30/t	0.227	0.358	57.7	+9.8
	MR$40/t (B)	0.242	0.358	47.9	0.0
	MR$50/t	0.265	0.358	39.3	-15.5
Manpower	MR$1600/y	0.237	0.356	50.2	+2.3
	MR$1800/y (B)	0.242	0.358	47.9	0.0
	MR$2000/y	0.247	0.361	46.2	-1.7
Maintenance (Gasifier)	MR$0.012/kWh	0.241	0.358***	48.5	+0.6
	MR$0.0125/kWh (B)	0.242	0.358	47.9	0.0
	MR$0.0130/kWh	0.242	0.359	48.3	+0.4
Lubricants	MR$2.00/l	0.239	0.356	48.9	+1.0
	MR$2.50/l	0.242	0.358	47.9	0.0
	MR$3.00/l	0.245	0.360	46.9	-1.0

* Baseline assumption
** For diesel engine, life-span variation is taken as 12y, 15y (B), 18y
*** For diesel engine, maintenance cost is MR$0.006, 0.00625 (B), 0.00650/kWh

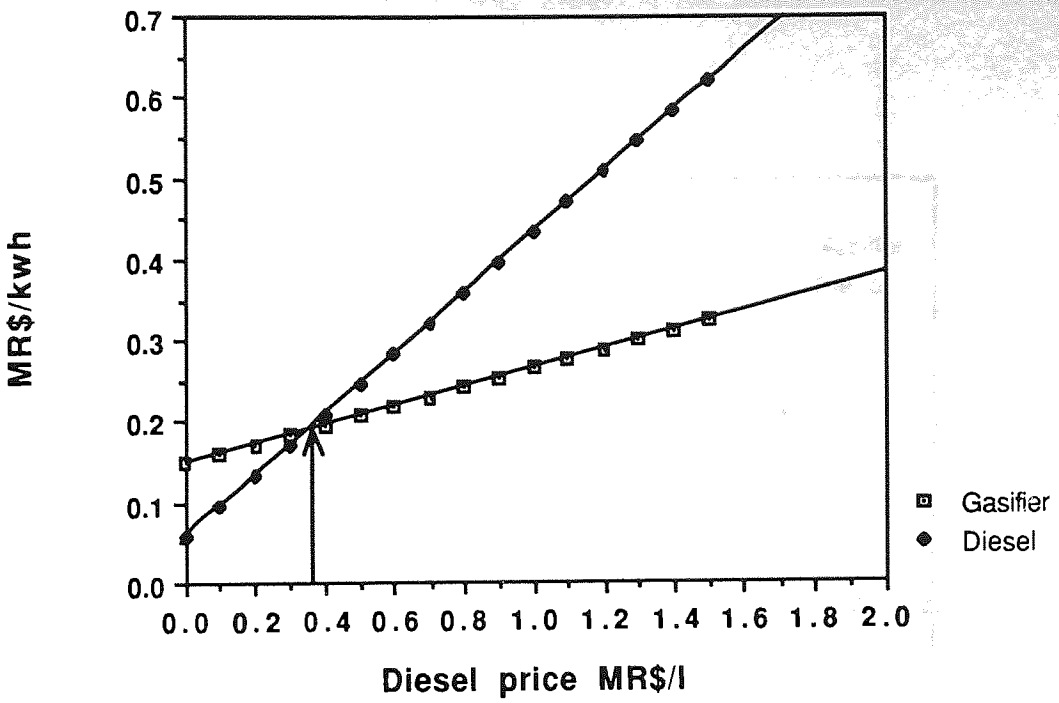


Figure 7.1 Effect of different diesel price on production cost

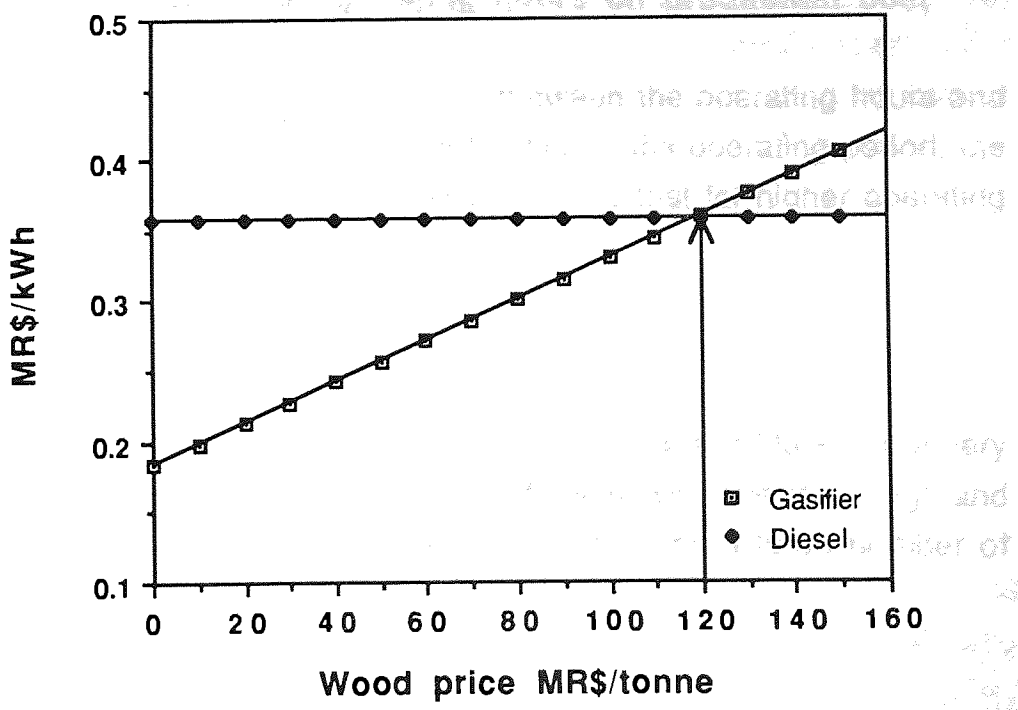


Figure 7.2 Effect of different wood price on production cost

The same conclusion can drawn from Figure 7.2 which indicated that gasification is only more attractive than diesel if the price of wood is less than MR$120/t.

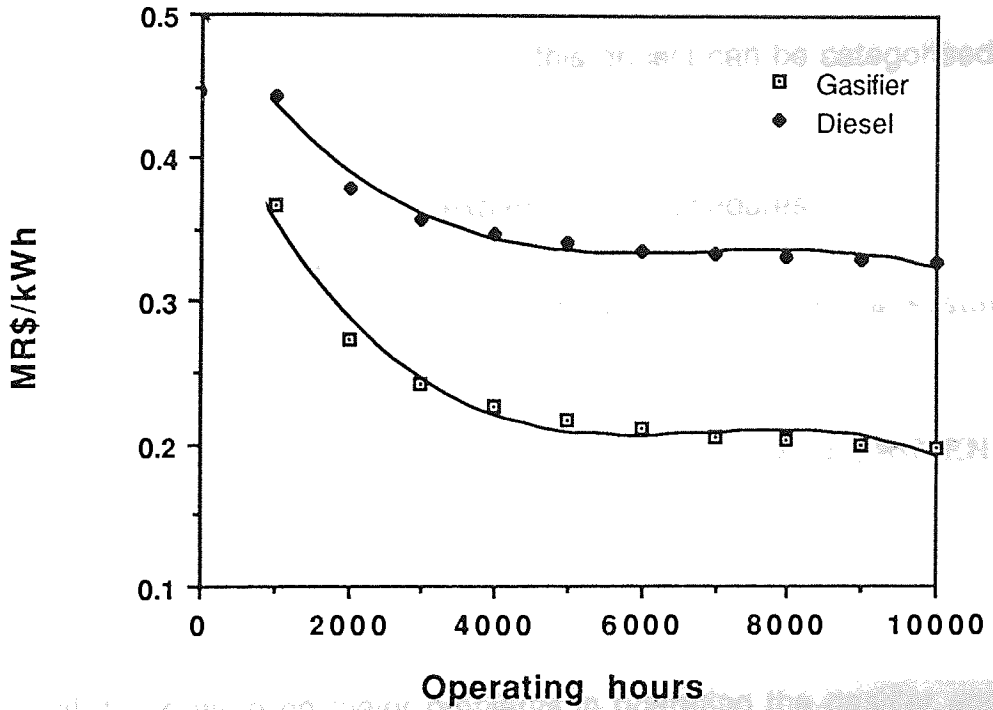


Figure 7.3 Effect of operating hours on production cost

Figure 7.3 illustrates that the relationship between the operating hours and the cost of production. It indicates that the higher the operating period, the lower will be the production cost. It also indicates that for higher operating periods the lower will be the production cost.

7.4 CONCLUSION

For the gasification system to be economically attractive in Malaysia, a very specific situation will be needed. The price of diesel will have to be high and the gasifier will be operated with high load factors and a large number of annual operating hours.

CHAPTER 8

CONCLUSIONS

8.1 CONCLUSIONS

The conclusions that can be drawn from this project can be categorised into three parts, namely:

1) Gasifier/engine system and experimental procedures
2) Experimental results
3) Identification of opportunities for implementing such a system in Malaysia

8.2 GASIFIER/ENGINE SYSTEM AND EXPERIMENTAL PROCEDURES

8.2.1 Gasifier performance in general

In general, there were no major problems in operating the gasifier and the instrumentation employed proved to be satisfactory. All the experimental objectives listed in Table 6.10 were successfully carried out in 101 runs and very valuable data were acquired on the gasification of rubberwood under different operating conditions. It is concluded that the gasifier is adequately designed to cope with rubberwood as feedstock.

Valuable experience were gained in the design and operation of the gasifier and its operational problems. Although there were no major problems in operating the gasifier, a number of operational difficulties and possible areas for improvement were identified and can be summarised as follows:

Gasifier

During the experimental programme, there was no major breakdown of the gasifier, apart from simple problems caused by air leakage and occasional careless handling of the gasifier. However, the following repairs were done during the experimental programme:

Cracks in the refractory lining was observed after 300 hours of operation and had to be repaired.

The inner parts of the air injector nozzles were found to have been eroded and had to be replaced after 500 hours of operation

Gas cleaning system

The combination of the cyclone dust separator and the box filter is probably adequate as a gas cleaning system as there was no problem operating the product gas on dual fuel. However, the presence of carbon and slag on top of the pistons (see section 6.22.4) indicates that carbon and tar particles were not filtered out.

It was also found that the wood and charcoal filter medium needs to be replaced every day due to large quantities of tar deposited on them. However, from the serviceability point of view, the design is very good as the filter trays can be replaced within a few minutes.

Air-gas cooler

During the experimental programme, it was difficult to obtain a gas temperature of less than 40 °C. The capacity of the cooler is probably not sufficiently to ensure that the gas is sufficiently cooled before it is introduced into the engine.

Tars condensed on the vertical pipes of the air-cooled condenser are difficult to remove and the tar deposit reduced the efficiency of the cooler.

Air-gas mixer

Control of the air-gas mixer is manual and it was found that this simple system worked very well. However, a certain degree of experience is needed to ensure that the correct mixing ratio is achieved.

Flanges

Occurrence of air leakage through connecting flanges of the piping system. Although the leaks could be stopped by tightening the bolts, it is difficult to carry out during gas operation due to concern over leaking toxic gases.

Starting fan

During start-up, large quantities of tars were found to condense on the fan blade and the rotor motor of the fan. The fan will have to be have to be cleaned regularly otherwise the condensed tar will cause problems to the rotor motor. During the experimental programme, two fans were replaced due to problems associated with high tar levels during start-up.

Engine

The maximum output achieved by the gasifier/engine generating system on dual fuel was 33.5 kWe, close to the maximum expected capacity of 35 kWe. The major repair on the engine was a broken piston ring which occurred in run 65.

After about 550 hours of operating the engine on dual fuel, there was no visible effects of producer gas on the engine valves, valve seats and guides and the injector nozzles. In view of the large number of start-ups and shut-downs, which subjected the engine to severe test, the result is therefore encouraging although the long term effects of operating the diesel engine on producer gas could not be established in this research.

There was also an increased in the composition of trace metals in the engine oil indicating a higher degree of engine wear.

8.2.2 Experimental procedures

Tar problem during operation

Due to the presence of tars in the product gas, problems were encountered in the measurement of the product gas, flowrate through the gas flowmeter. The tar content in the product gas which condensed in the inlet manifold of the gas flowmeter proved to be particularly difficult to remove and this factor has limited the accuracy of the data to be collected.

Feeding mechanism

The wood flowrate was measured by simply timing the rate of batches of wood added into the gasifier. The feeding process was not only time consuming process but was often dangerous to the operator due to the possibility of carbon monoxide leaking out from the gasifier. A more effective

feeding system will have to be found and this is discussed in the recommendations in Chapter 9.

Tar recovery system

The tar recovery system was found to be inadequate as tars condensed on the inner parts of the pipes were not recovered and this resulted in a major loss of tars for mass and energy determination. Furthermore, the present method of separating tars from condensate proved inefficient and is a very slow and tedious task.

Temperature measurements

The thermocouples located inside the gasifier had caused the formation of voids and bridging of particles and so were removed. It would be useful to have a more "non-invasive" method of temperature measurement.

Limitation in power output of the diesel engine

It was found the gasifier was able to handle at least 1.5 times its design capacity. However, the engine was not able to cope with the maximum capacity of the gasifier due to its limited power output. With the present set-up, the gasifier/engine system is only able to be operated at 60-70 % of its maximum capacity for stable operation (see section 8.3.5).

8.3 EXPERIMENTAL RESULTS

8.3.1 Mass, energy and elemental closures

The overall average mass closure was 92.7 % and the overall elemental closures of carbon, oxygen and hydrogen balances for all the runs were found to be 91.13 %, 89.30 % and 100.35 % respectively. These values are within the range of 85-110 % reported in the literature. The lower closure of oxygen is believed to be due to uncertainty in the determination of the tar and condensate yield from the gasifier.

The overall average energy balances over the gasifier was 98.66 % while the overall average energy balance of the gasifier to cold clean gas was 102.36 %. For the gasifier/engine system, the average overall energy balance was found to be 101.90 %. These values are well within the range of 85-110 % reported in the literature.

8.3.2 Heat losses from gasifier

The lowest and highest total heat loss from the gasifier was found to be 10 % and 26 % of the chemical energy of wood. The total highest and lowest heat loss from the complete system to cold clean gas was found to be 17 % and 37 % of the chemical energy of wood. For the capacity of the gasifier of this size, the heat losses estimations are within the range reported by Kjellstrom, (1985).

8.3.3 Results

Based on the experimental data, the average gas heating value for all the runs was found to be 4.95 MJ/Nm^3. The average overall cold gas efficiency for all the runs was found to be 47.5 %.

The power output from the engine was found to be from 5 to 33.5 kWe. The average diesel displacement of dual fuel engine was found to be 68.5 % while the average thermal efficiency was found to be 17.8 %.

8.3.4 Gasifier turndown and the "bubble theory"

It was found that the gasifier be readily turned down and a maximum turndown ratio of up to 5 was obtained. Two novel hypotheses are proposed to account for the phenomena of turndown.

The first hypothesis is an arched reaction zone shell above the throat. It is suggested that the reaction zone grows into a hemispherical shell around the throat as gas demand increases. The second hypothesis is a reaction zone in the form of a "bubble" between or around the air injectors. This "bubble" will grow into a spherical or ovoid shell as gas demand increases. At high capacity, these two hypotheses merge.

From the experimental results, it was also concluded, that at low capacity, the "bubble" is too small and allowed for the existence of cold spots from which pyrolytic gas passes through uncracked. At very high capacity above the operational limit of the gasifier, the "bubble" becomes unstable and finally disintegrates allowing pyrolytic gas to pass through uncracked.

8.3.5 Qualitative and quantitative results

For this research, the performance of the gasifier was evaluated by the gas heating value, cold gas efficiency and the power output of the engine. The conclusions of the parameters investigated are summarised as follows:

Influence of moisture content on gasifier performance

Contrary to most reported literature, it was found that wood of a moisture content of up to 51.5 % (wet basis) was successfully gasified.

From the research data, the optimum condition for operating the gasifier will be rubberwood of low moisture content (less than 10 % wet basis), with wood of size 3 cm x 3 cm x 1 cm. For stable power output, the gasifier should between 60-70 % of the dry wood capacity.

It was also found that for the same moisture content, there was no significant influence of particle size on the cold gas efficiency, gas heating value and the power output of the gasifier.

For wood of size 3 cm x 3 cm x 1 cm and 3 cm x 3 cm x 3 cm, the gas heating value, cold gas efficiency, and power output was found to decrease as moisture in wood increases. These observations are in agreement with the water shift reaction.

Influence of dry wood capacity on gasifier performance

The maximum throughput of the gasifier for stable operation was found to be 60-70 % of the maximum dry wood capacity because of the "bubble" effect.

It was also found that the gasifier was able to handle at least 1.5 times its design capacity. However, this capacity was not achieved during the research due to limitations of the engine to handle higher throughputs.

Influence of particle size on gasifier performance

It was found that the smallest wood size resulted in higher cold gas efficiency compared to bigger wood size. For wood of the same size, the cold gas efficiency was generally found to be better when operated at higher capacity.

It was also found that regularly shaped particles gave better gas heating value of the gas compared with irregularly shaped particle. This supports the hypothesis that the shape of the particle is an important criterion in the performance of the gasifier.

Influence of number of nozzles and throat diameter on tar cracking

Contrary to most reported literature, it was found that more uniform air distribution through the use six air injector nozzles instead of three did not improve the tar cracking ability of the gasifier. It thus confirmed that the oxygen penetration depth in the fuel bed is probably very limited and may be in the order of two to five particles diameter from the point of ignition, as reported for open core gasifiers.

A decrease in the throat diameter of the reactor by half also did not improved the tar cracking ability of the gasifier. Decrease in the throat diameter was found to cause bridging which gave rise to the occurrence of voids which allowed tar laden gas to pass through uncracked.

Influence of dry wood capacity on engine performance

For a dry wood capacity of less than 60 % of maximum dry wood capacity, it was found that the thermal efficiency of the engine was between 17-18 %. Within this range, the thermal efficiency was found to be independent of the dry wood capacity. However, above a dry wood capacity of 60 %, the thermal efficiency of the engine decreased rapidly with dry wood capacity. This behaviour provided further evidence on the disintegration of the "bubble" which will lead to the a corresponding increase in the tar content of the product gas and a decrease in the thermal efficiency of the engine.

For dry wood capacity of below 60 %, the diesel displacement was found to increase with dry wood capacity. However, above a wood capacity of 60 %, the diesel displacement was found to decrease with dry wood capacity due to the disintegration of the "bubble".

8.4 IDENTIFICATION OF OPPORTUNITIES OF SUCH A RUBBERWOOD GASIFIER-POWER SYSTEM IN MALAYSIA

8.4.1 Total quantity of rubberwood residues available

The total quantity of rubberwood residues available in the country is estimated to range from 15 to 60 million tonnes per year from 1988-2000. Based on various possible scenarios of a 0 %, 5 %, 10 % and 15 % annual increment in demand of rubberwood residues, there will still be substantial quantity of rubberwood residues that remained under utilised.

8.4.2 Potential of gasification system in Malaysia

The production cost of generating electricity from the rubberwood gasifier and diesel system was found to be MR$0.242/kWh and MR$0.358/kWh respectively. Based on a sensitivity analysis, it was concluded that the main factors that will influence the production cost are annual operating hours and cost of diesel and wood.

The gasification system/engine system for generating electricity will only be cheaper than diesel if wood price is less than MR$120/tonne and the diesel price must be greater than MR$35/l. The gasifier will also have to be operated for at least 3000 hours per year.

The States that may have the biggest opportunity for implementing gasification technology are Johore, Negri Sembilan and Perak.

CHAPTER 9

RECOMMENDATIONS

9.1 SYSTEM MODIFICATION

During the research work, a number of possible modifications in the gasifier system were identified to improve reliability of the gasifier. These recommendations are as follows:

1) With the present design of the gasifier, wood is fed into the gasifier manually. One operator has to be exclusively assigned to feeding and keeping a proper record of the wood feedrate of the process. This method of recording the feedrate was a very timing consuming process. Furthermore the process of feeding involves opening the gate valve at the base of the hopper which allows air to leak into the gasifier. This can be dangerous if an engine breakdown occurs during the feeding process. The uncontrolled addition of air can cause the gasifier to detonate and cause injury to the operator. This happened twice during the research.

2) The feeding system can be considerably simplified by the use of a mechanical system such as a screw feeder system which can feed wood mechanically into the gasifier thus overcoming the above problems. Such a system could be electrically driven.

3) The strength of the refractory lining can be further reinforced by the use of steel wires mixed with the refractory. Another possibility is the use of a refractory lining cast in loose blocks so that it can be easily replaced.

4) The capacity of the air-cooled condenser was inadequate and the use of a larger air-cooled condenser is recommended. It is also recommended that larger diameter pipes be used to facilitate cleaning of the cooler.

5) The present air-gas mixer for the engine should be replaced by a carburettor or an auxiliary governor to control the air-fuel mixture. This is especially important when no operators are in attendance. Coovattanachai, (1989) reported the development of such a governor, but no information is available on the reliability.

6) The use of flexible joints and connections for the existing pipe work will probably reduce the air leakage problem.

7) The air injector nozzles can be fitted with a cast iron sleeve for reduced corrosion and easier replacement.

9.2 FUTURE WORK

This study has also identified a number of areas for future work in order to be able to collect more information on the gasification process. The following are recommended to receive particular attention:

9.2.1 System scale-up

As mentioned earlier in terms of wood throughput, the gasifier was was able to handle at least 1.5 times its design capacity. In order to acquire the maximum capacity of the gasifier, it is recommended that a bigger capacity engine be used in future work. It is recommended that a 50 kWe diesel engine be used.

9.2.2 Measurement of air flowrate

In order to enhance the accuracy of the mass and energy balance, an accurate air input rate must be measured. It is recommended that an orifice plate be installed at the air inlet port in order to be able to collect more accurate data on air input into the gasifier.

9.2.3 Measurement of the nitrogen content of air

To improve on the accuracy of the mass balance, it is proposed that the nitrogen content in the product gas and be measured accurately by a nitrogen analyser.

9.2.4 Measurement of wood feedrate

It is recommended that a more accurate way of recording the wood feedrate by installed. The screw feeder system recommended earlier would have to be calibrated to measure wood feedrate accurately. However, it must be

able to be programmed to cope with different wood sizes and a wide range of feedrates.

9.2.5 Additional temperature measurement

In order to understand the mechanism of turndown and limited carbon conversion (section 5.5 of chapter 5), it is recommended that in-bed temperature at the oxidation zone be measured as accurately as possible both radially and vertically. The present method of measuring the temperature at the oxidation and reduction zone by the use of thermocouples tends to be unreliable for a number of reasons. The temperature can represent the temperature of the solid particle if the probe touches the surface of a solid particle or the gas temperature in a gas space. It is also strongly influenced by local radiation heat transfer. An alternative method such as the use of an optical pyrometer can be installed at the sight glass to monitor the temperature profile of oxidation and reduction zone.

Measurements of the surface temperature at different heights of the gasifier outer wall and at the different surfaces of the gas cooling and cleaning system are needed to improve the estimation of heat losses from the gasifier.

9.2.6 Heat losses

It was found that many of the effects of the gasification processes in the gasifier are masked by the reactor heat loss such as by radiation and convection. Hence, experiments should be performed by with an insulated reactor. This will allow for a more detailed investigation of the effect of heat loss on gasifier performance such as tar cracking capability and reactor turndown. The data will also be useful to check the energy balance of the system.

9.2.7 Bed vibrating system

A bed stirring system in the form of a mechanical agitator should be installed inside the gasifier to help to break up bridging and to prevent the formation of voids. The agitator can be in the form of a vibrating ring located above the air nozzles. The same mechanism have been successfully tried by the

Pacific Class gasifier developed by Fluidyne Ltd. of New Zealand (Williams, 1989).

9.2.8 Long term effect of producer gas on engine

Although this research has succeeded in operating a diesel engine on producer gas, it is important to operate the gasifier for a longer period in order to order to ascertain the long term effect of producer gas on the lifespan of the engine. It is proposed that the gasifier be loaned to one of the small holders development programme for an operational period of 2-3 years in order to be able to fully assess its long term effect on the engine.

9.2.9 Other modifications

Other modifications that might be made but are of a lower priority are:

Sulphur content of product gas

Rubberwood has a sulphur content of 0.1 % by weight (Table 6.5). To ensure the long term reliability of the gasifier in terms of corrosion problem associated with sulphur in the product gas, measurement of the sulphur content is important to devise sulphur cleaning systems if the permissible sulphur content is too high.

Measurement of dust and tar content of product gas

The engine is very sensitive to the tar and dust levels of the product gas. For this research, no method was design to measure these contaminants. It is recommended that an accurate tar and dust sampler be installed at different parts of the gas cooling and cleaning system in order to monitor the efficiency of the cleaning and to ensure that tarry and dirty gas do not get into the engine. There are however no known commercial dust and tar samplers available for this purpose. The only method that is being used by monitoring programme of The World Bank is the THT dust and tar sampling device developed by Twente University in The Netherlands (World Bank 1988). It is recommended that tar and dust sampler be installed for future work.

9.3 Economic assessment of gasification systems in Malaysia

In order to have a more accurate economic assessment of the potential of gasification systems in Malaysia, more information on total plant costs of a gasification system including storage, handling, installation and waste disposal should be collected. Another possibility is to investigate the use of producer gas for the production of liquid fuels and chemicals such as methanol.

APPENDIX I

Published work

Papers presented at 6th European Conference on "Biomass For Energy, Industry and Environment", 22-26 April 1991, Athens, Greece.

APPENDIX II

Physical and chemical properties data for rubberwood of size from 3 cm x 3 cm x 1 cm to 3 cm x 3 cm x 6 cm

	A	B	C	D	E	F	G
1	**3x3x1**	**1**	**2**	**3**	**4**	**Average**	**STD**
2	M.C (%)	7.7	8.2	8.5	8.3	8.2	0.3
3	Abs.density	645.0	697.0	679.0	688.0	677.3	19.7
4	Bulk density	305.0	313.0	298.0	300.0	304.0	5.8
5	Cellulose	44.5	42.7	46.8	44.8	44.7	1.5
6	Lignin	22.8	24.6	22.3	22.6	23.1	0.9
7	Pentosan	17.8	17.3	15.9	16.4	16.9	0.7
8	Water soluble	6.1	5.7	7.4	7.3	6.6	0.7
9	Others	9.1	9.7	7.6	8.9	8.8	0.8
10	C	48.5	48.5	47.9	47.7	48.2	0.4
11	H	5.7	5.6	5.3	5.2	5.5	0.2
12	O	44.3	44.7	44.9	45.7	44.9	0.5
13	N	0.10	0.10	0.20	0.10	0.13	0.04
14	S	0.10	0.10	0.10	0.20	0.13	0.04
15	Ash	1.3	1.0	1.6	1.1	1.3	0.2
16	Volatile matte	79.4	78.5	80.2	76.9	78.8	1.2
17	Ash	1.2	1.4	1.0	1.5	1.3	0.2
18	Fixed carbon	19.4	20.1	18.8	21.6	20.0	1.0
19	HHV (IGT)	**18738.5**	**18562.8**	**17916.1**	**17646.1**	**18215.9**	**449.5**
20	HHV (data)	**18055.0**	**18013.0**	**18536.0**	**18423.0**	**18256.8**	**226.8**
21							
22							
23	**3x3x2**	**1**	**2**	**3**	**4**	**Average**	**STD**
24	M.C (%)	8.0	8.2	8.4	7.9	8.1	0.2
25	Abs.density	639.0	688.0	680.0	678.0	671.3	19.0
26	Bulk density	301.0	302.0	290.0	291.0	296.0	5.5
27	Cellulose	44.1	44.5	46.3	45.9	45.2	0.9
28	Lignin	23.7	23.2	21.3	22.9	22.8	0.9
29	Pentosan	18.5	17.2	16.3	16.7	17.2	0.8
30	Water soluble	5.5	5.1	6.5	6.4	5.9	0.6
31	Others	8.2	10.0	9.6	7.8	8.9	0.9
32	C	48.3	48.5	48.3	49.0	48.5	0.3
33	H	5.6	5.9	5.7	5.3	5.6	0.2
34	O	44.8	44.2	44.6	44.3	44.5	0.2
35	N	0.00	0.10	0.10	0.10	0.08	0.04
36	S	0.10	0.10	0.20	0.20	0.15	0.05
37	Ash	1.2	1.2	1.1	1.1	1.2	0.1
38	Volatile matte	81.3	80.5	78.7	80.6	80.3	1.0
39	Ash	1.3	0.9	1.4	1.4	1.3	0.2
40	Fixed carbon	17.4	18.6	19.9	18.0	18.5	0.9
41	HHV (IGT)	**18491.5**	**19016.6**	**18644.2**	**18389.7**	**18635.5**	**238.0**
42	HHV (data)	**18922.1**	**19183.0**	**18977.1**	**18028.0**	**18777.6**	**443.5**

	H	I	J	K	L	M	N
1	3x3x3	1	2	3	4	Average	STD
2		7.8	8.1	7.9	7.8	7.9	0.1
3		632.0	691.0	675.0	680.0	669.5	22.4
4		298.0	298.0	290.0	290.0	294.0	4.0
5		44.5	45.2	44.8	45.3	45.0	0.3
6		22.9	23.2	21.6	21.8	22.4	0.7
7		17.0	17.7	17.1	17.2	17.3	0.3
8		6.4	4.7	6.7	6.8	6.2	0.9
9		9.2	9.2	9.8	8.9	9.3	0.3
10		48.4	47.5	48.4	47.8	48.0	0.4
11		5.1	5.1	5.3	5.7	5.3	0.2
12		44.2	45.8	43.9	44.6	44.6	0.7
13		0.10	0.10	0.10	0.10	0.10	0.00
14		0.10	0.10	0.10	0.20	0.13	0.04
15		2.1	1.4	2.2	1.6	1.8	0.3
16		81.2	78.5	78.9	82.4	80.3	1.6
17		1.6	1.4	1.5	1.2	1.4	0.1
18		17.2	20.1	19.6	16.4	18.3	1.6
19		17910.4	17422.2	18209.4	18466.0	18002.0	388.2
20		18600.9	18263.7	18716.0	18737.5	18579.5	189.6
21							
22							
23	3x3x4	1	2	3	4	Average	STD
24		7.9	8.3	7.5	7.4	7.8	0.4
25		645.3	678.0	693.0	683.0	674.8	17.9
26		285.0	288.0	285.0	285.3	285.8	1.3
27		44.6	45.1	44.9	45.9	45.1	0.5
28		22.9	22.8	22.6	23.1	22.9	0.2
29		17.6	17.5	15.7	15.8	16.7	0.9
30		6.4	5.4	6.5	6.4	6.2	0.4
31		8.5	9.2	10.3	8.8	9.2	0.7
32		48.6	47.4	47.5	47.8	47.8	0.5
33		5.8	4.8	6.1	5.3	5.5	0.5
34		44.0	46.1	44.6	44.8	44.9	0.8
35		0.10	0.10	0.10	0.10	0.10	0.00
36		0.10	0.10	0.10	0.10	0.10	0.00
37		1.4	1.5	1.6	1.9	1.6	0.2
38		82.1	79.3	80.2	79.7	80.3	1.1
39		1.2	1.5	1.3	1.0	1.3	0.2
40		16.7	19.2	18.5	19.3	18.4	1.0
41		18939.4	16953.7	18886.1	17901.4	18170.1	814.9
42		18152.4	18033.1	18860.7	18482.0	18382.1	321.6

	O	P	Q	R	S	T	U
1	3x3x5	1	2	3	4	Average	STD
2		7.6	8.5	7.3	7.1	7.6	0.5
3		640.4	688.4	680.0	678.5	671.8	18.5
4		280.0	280.0	279.0	280.0	279.8	0.4
5		44.3	45.1	45.9	44.9	45.1	0.6
6		22.9	22.8	20.9	21.7	22.1	0.8
7		16.9	16.8	15.7	16.5	16.5	0.5
8		6.1	5.3	6.5	0.0	4.5	2.6
9		9.8	10.0	11.0	16.9	11.9	2.9
10		49.5	49.3	48.9	47.8	48.9	0.7
11		5.1	5.5	5.5	5.6	5.4	0.2
12		43.8	43.5	43.5	44.8	43.9	0.5
13		0.10	0.10	0.10	0.10	0.10	0.00
14		0.10	0.10	0.10	0.10	0.10	0.00
15		1.4	1.5	1.9	1.6	1.6	0.2
16		81.3	80.5	79.4	80.6	80.5	0.7
17		1.4	1.3	1.2	1.4	1.3	0.1
18		17.3	18.2	19.4	18.0	18.2	0.8
19		18344.2	18839.7	18697.1	18302.9	18546.0	228.5
20		18104.7	18258.2	18066.5	18682.5	18278.0	244.3
21							
22							
23	3x3x6	1	2	3	4	Average	STD
24		7.3	8.0	7.3	7.5	7.5	0.3
25		645.3	690.3	679.4	680.0	673.8	17.0
26		276.0	276.0	274.0	275.3	275.3	0.8
27		44.5	44.9	45.2	45.9	45.1	0.5
28		22.8	24.1	20.9	21.6	22.4	1.2
29		17.4	16.5	17.3	15.6	16.7	0.7
30		6.8	5.1	6.8	7.3	6.5	0.8
31		8.5	9.4	9.8	9.6	9.3	0.5
32		48.9	49.6	48.4	48.6	48.9	0.5
33		5.8	5.2	5.5	5.7	5.6	0.2
34		43.1	43.6	44.2	43.6	43.6	0.4
35		0.10	0.10	0.10	0.10	0.10	0.00
36		0.10	0.10	0.10	0.10	0.10	0.00
37		2.0	1.4	1.7	1.9	1.8	0.2
38		81.1	80.5	81.2	79.9	80.7	0.5
39		1.5	1.4	1.2	1.4	1.4	0.1
40		17.4	18.1	17.6	18.7	18.0	0.5
41		19140.5	18534.6	18445.7	18847.4	18742.1	274.2
42		18243.0	18207.6	18868.0	18062.1	18345.2	309.4

APPENDIX III

Raw data for runs 1-101

	A	B	C	D	E	F	G	H
1	Runs	Wood	Moisture	Feed	CO2	H2	CH4	CO
2		size	content	rate				
3			(wb)	(wet)				
4		cm	(%)	(kg/h)	(%)	(%)	(%)	(%)
5	R1	3x3x1	10.2	43.5	11.0	10.0	9.0	15.5
6	R2	3x3x1	21.2	44.5	14.0	10.0	3.0	12.0
7	R3	3x3x1	31.5	42.9	17.0	5.0	4.0	8.0
8	R4	3x3x1	42.4	50.3	23.0	2.0	2.0	5.0
9	R5	3x3x1	51.6	51.5	25.0	1.0	1.0	3.5
10	R6	3x3x6	9.8	46.7	10.5	9.5	9.0	15.0
11	R7	3x3x6	19.5	46.5	12.5	9.0	5.0	13.5
12	R8	3x3x6	32.5	47.8	16.5	6.0	2.5	9.5
13	R9	3x3x6	42.4	49.3	18.5	4.0	2.0	5.0
14	R10	3x3x6	52.4	52.5	20.5	1.0	1.0	3.5
15	R11	3x3x1	NA	44.3	11.5	9.3	0.9	16.7
16	R12	3x3x1	10.6	45.4	14.0	14.0	1.3	25.0
17	R13	3x3x1	22.5	46.5	18.5	15.5	1.4	19.5
18	R14	3x3x1	30.5	47.5	20.0	15.0	1.3	16.5
19	R15	3x3x1	45.5	50.6	21.0	18.0	1.0	12.0
20	R16	3x3x1	52.3	52.0	21.0	20.0	1.3	7.0
21	R17	3x3x6	10.9	47.5	13.5	12.0	1.1	22.3
22	R18	3x3x6	21.5	48.5	18.0	11.0	1.3	18.5
23	R19	3x3x6	31.5	51.4	19.5	9.5	1.2	15.0
24	R20	3x3x6	40.8	54.2	21.0	8.0	1.5	10.6
25	R21	3x3x6	52.5	57.0	21.0	8.0	1.4	8.5
26	R22	3x3x1	8.8	8.5	13.0	13.5	0.8	11.6
27	R23	3x3x1	9.9	16.2	12.8	14.5	0.8	14.6
28	R24	3x3x1	8.9	26.2	12.6	15.5	0.7	16.9
29	R25	3x3x1	10.3	33.5	12.3	18.4	0.6	18.9
30	R26	3x3x1	9.8	35.7	12.2	17.8	0.4	21.9
31	R27	3x3x1	10.4	42.8	11.9	15.9	0.5	21.9
32	R28	3x3x1	10.7	48.6	10.5	17.2	0.6	22.4
33	R29	3x3x1	9.8	65.8	9.9	18.5	0.5	23.5
34	R30	3x3x2	9.8	10.3	12.4	15.5	0.8	16.5
35	R31	3x3x2	9.6	19.4	11.2	16.5	0.7	21.3
36	R32	3x3x2	10.3	27.2	10.8	16.3	0.7	23.0
37	R33	3x3x2	10.6	34.5	9.8	17.7	0.8	24.1
38	R34	3x3x2	10.8	39.7	9.3	16.9	0.7	23.9
39	R35	3x3x2	10.2	45.3	9.1	17.9	0.7	24.5
40	R36	3x3x2	8.9	49.4	8.9	18.5	0.9	24.8
41	R37	3x3x2	8.7	55.6	8.8	17.8	1.2	25.2
42	R38	3x3x2	9.3	65.3	8.6	18.5	1.1	25.7
43	R39	3x3x3	9.5	10.6	11.4	16.2	0.8	18.7
44	R40	3x3x3	8.9	20.7	9.0	16.5	0.9	20.6
45	R41	3x3x3	10.3	29.0	8.6	15.5	0.9	24.5

	A	B	C	D	E	F	G	H
46	R42	3x3x3	9.6	35.3	8.5	16.7	1.2	26.7
47	R43	3x3x3	10.1	42.9	8.5	17.3	0.9	28.5
48	R44	3x3x3	10.2	50.7	8.1	17.4	1.4	29.2
49	R45	3x3x3	9.7	55.9	8.2	16.9	1.3	28.9
50	R46	3x3x3	10.5	65.5	7.9	16.9	1.3	29.7
51	R47	3x3x3	9.1	75.3	7.8	16.5	1.5	29.5
52	R48	3x3x4	8.2	16.0	11.5	16.7	0.9	15.3
53	R49	3x3x4	9.6	23.4	10.5	17.1	0.8	18.5
54	R50	3x3x4	10.0	25.4	9.5	16.9	1.1	20.8
55	R51	3x3x4	9.3	28.8	8.3	16.3	0.9	25.6
56	R52	3x3x4	9.1	35.5	7.9	16.7	1.4	27.8
57	R53	3x3x4	9.6	42.9	8.3	16.9	1.5	26.6
58	R54	3x3x4	9.4	52.5	8.5	17.1	1.8	26.1
59	R55	3x3x4	8.3	66.1	8.9	16.8	1.7	25.8
60	R56	3x3x4	10.2	72.4	9.1	16.9	1.3	25.1
61	R57	3x3x5	9.4	20.4	8.1	16.4	0.9	15.3
62	R58	3x3x5	8.6	29.5	8.5	16.5	1.1	16.3
63	R59	3x3x5	8.3	35.7	9.8	16.9	1.6	18.6
64	R60	3x3x5	9.4	43.7	9.2	17.3	1.8	20.5
65	R61	3x3x5	9.3	50.1	9.8	17.8	1.7	19.7
66	R62	3x3x5	9.2	70.2	9.6	17.1	1.9	18.5
67	R63	3x3x5	8.8	76.8	10.2	16.5	1.8	17.4
68	R64	3x3x5	8.6	85.0	11.3	16.4	2.1	17.1
69	R65	NA	NA	NA	NA	NA	NA	NA
70	R66	3x3x6	8.8	24.0	9.8	15.2	1.4	13.0
71	R67	3x3x6	9.8	32.6	11.5	15.6	1.8	13.9
72	R68	3x3x6	10.4	38.5	12.6	15.1	2.1	15.1
73	R69	3x3x6	9.3	45.7	13.2	15.1	2.1	14.8
74	R70	3x3x6	9.8	52.7	14.5	14.9	2.3	14.2
75	R71	3x3x6	9.9	59.8	15.9	14.8	2.5	13.7
76	R72	3x3x6	8.3	67.2	16.3	14.5	2.4	11.9
77	R73	3x3x6	9.6	75.8	16.8	14.6	2.6	11.6
78	R74	3x3x1	15.5	15.5	11.6	9.0	0.8	17.1
79	R75	3x3x1	16.4	17.4	12.7	10.4	0.7	17.1
80	R76	3x3x1	15.5	38.5	12.8	15.6	0.8	18.5
81	R77	3x3x1	17.5	42.3	13.2	16.3	0.7	19.1
82	R78	3x3x1	15.5	55.6	11.9	17.3	0.6	20.5
83	R79	3x3x1	16.0	54.6	10.2	15.6	0.6	21.3
84	R80	3x3x1	15.4	16.9	12.8	13.5	0.8	17.3
85	R81	3x3x1	16.5	15.6	11.9	12.6	0.9	18.3
86	R82	NA	NA	NA	NA	NA	NA	NA
87	R83	3x3x1	16.8	43.5	15.2	11.4	0.7	20.5
88	R84	3x3x1	14.6	53.6	12.5	12.8	0.7	20.8
89	R85	3x3x1	15.6	58.9	11.8	14.5	0.8	21.2

	A	B	C	D	E	F	G	H
90	R86	3x3x1	8.5	42.3	15.5	14.8	1.1	22.4
91	R87	3x3x1	18.9	41.8	15.4	15.5	1.2	18.5
92	R88	3x3x1	31.3	39.5	14.5	13.6	1.0	16.8
93	R89	3x3x1	43.6	38.9	12.1	12.5	1.3	12.3
94	R90	3x3x1	51.5	41.1	11.0	13.0	1.3	6.9
95	R91	3x3x3	9.2	42.3	13.5	12.7	1.0	20.5
96	R92	3x3x3	18.6	40.5	16.3	12.9	0.9	16.8
97	R93	3x3x3	31.6	38.5	20.7	10.6	0.9	14.6
98	R94	3x3x3	43.5	41.2	22.4	9.5	1.1	10.3
99	R95	NA	NA	NA	NA	NA	NA	NA
100	R96	3x3x1	15.7	18.9	14.0	15.2	1.3	14.7
101	R97	3x3x1	16.4	28.9	13.5	16.5	1.1	15.7
102	R98	3x3x1	14.8	34.1	13.0	17.3	0.9	16.0
103	R99	3x3x1	15.9	50.3	12.5	17.8	1.0	16.8
104	R100	3x3x1	15.3	57.9	10.8	18.7	1.0	18.4
105	R101	3x3x1	14.9	63.4	9.9	18.9	1.1	20.0

	I	J	K	L	M	N	O	P
1	N2	Gas	Electric	Volume	Tar	Char	Ash	Conden-
2		flowrate	energy	of diesel	output	output	output	sate
3			(out)	used				output
4	(%)	(Nm3/h)	(KW)	(l/h)	(kg/h)	(kg/h)	(kg/h)	(kg/h)
5	54.5	94.2	NA	NA	NA	NA	NA	NA
6	61.0	89.5	NA	NA	NA	NA	NA	NA
7	66.0	85.6	NA	NA	NA	NA	NA	NA
8	68.0	98.6	NA	NA	NA	NA	NA	NA
9	69.5	99.5	NA	NA	NA	NA	NA	NA
10	56.0	73.4	NA	NA	NA	NA	NA	NA
11	60.0	85.5	NA	NA	NA	NA	NA	NA
12	65.5	87.5	NA	NA	NA	NA	NA	NA
13	70.5	90.4	NA	NA	NA	NA	NA	NA
14	74.0	102.5	NA	NA	NA	NA	NA	NA
15	61.6	127.1	NA	NA	NA	NA	NA	NA
16	45.7	87.7	NA	NA	NA	NA	NA	NA
17	45.1	94.3	NA	NA	NA	NA	NA	NA
18	47.2	102.3	NA	NA	NA	NA	NA	NA
19	48.0	96.3	NA	NA	NA	NA	NA	NA
20	50.7	90.5	NA	NA	NA	NA	NA	NA
21	51.1	96.7	NA	NA	NA	NA	NA	NA
22	51.2	103.5	NA	NA	NA	NA	NA	NA
23	54.8	107.8	NA	NA	NA	NA	NA	NA
24	58.9	109.5	NA	NA	NA	NA	NA	NA
25	61.1	97.6	NA	NA	NA	NA	NA	NA
26	61.1	25.0	4.6	0.566	0.35	0.84	0.07	0.92
27	57.3	43.2	9.3	1.116	0.97	1.09	0.13	1.79
28	54.3	73.0	17.4	2.044	0.99	1.34	0.21	1.60
29	49.8	89.3	22.8	2.636	0.98	1.07	0.35	1.69
30	47.7	97.5	25.7	2.930	1.20	1.16	0.32	1.32
31	49.8	113.6	28.5	3.192	1.33	1.13	0.33	1.60
32	49.3	115.4	26.1	2.936	2.68	2.03	0.36	3.12
33	47.6	112.2	23.8	2.737	3.46	3.49	0.52	6.25
34	54.8	24.7	5.6	0.691	0.95	0.89	0.08	1.99
35	50.3	40.0	10.9	1.333	1.33	1.46	0.15	2.21
36	49.2	59.7	16.2	1.962	1.89	1.68	0.21	2.34
37	47.6	72.9	21.2	2.533	1.98	1.94	0.26	3.62
38	49.2	88.9	25.4	2.997	2.16	2.02	0.31	4.16
39	47.8	106.4	30.8	3.542	1.43	2.47	0.35	4.17
40	46.9	112.2	32.8	3.739	2.74	2.57	0.39	4.41
41	47.0	113.0	32.0	3.680	3.56	3.56	0.43	4.82
42	46.1	120.0	28.4	3.351	3.89	4.76	0.51	6.04
43	52.9	20.4	5.3	0.689	0.97	1.12	0.08	1.96
44	53.0	43.2	10.8	1.382	1.79	1.78	0.16	2.55
45	50.5	55.8	15.9	1.988	1.96	2.26	0.24	2.97

	I	J	K	L	M	N	O	P
46	46.9	69.8	21.3	2.577	2.15	2.20	0.28	3.38
47	44.8	84.3	26.5	2.915	2.46	2.94	0.33	4.22
48	43.9	104.6	30.5	3.538	3.22	3.13	0.39	4.87
49	44.7	131.8	33.5	3.903	3.21	2.95	0.43	4.71
50	44.2	140.1	28.2	3.356	3.64	3.61	0.50	5.84
51	44.7	120.0	22.7	2.747	3.73	4.73	0.59	6.96
52	55.6	25.7	6.1	0.787	1.95	2.01	0.14	2.43
53	53.1	43.5	11.1	1.388	2.03	2.35	0.18	2.38
54	51.7	52.8	14.8	1.806	1.86	2.95	0.19	2.55
55	48.9	59.7	17.5	2.083	2.04	3.34	0.23	2.64
56	46.2	80.3	25.1	2.937	2.33	3.74	0.28	3.14
57	46.7	95.7	30.3	3.439	2.74	3.84	0.33	4.11
58	46.5	106.4	29.1	3.376	2.89	4.06	0.42	4.93
59	46.8	110.5	26.3	3.103	3.87	4.88	0.53	6.83
60	47.6	113.5	20.7	2.505	4.31	4.92	0.56	7.33
61	59.3	34.6	8.7	1.079	2.84	3.15	0.15	3.05
62	57.6	55.6	14.0	1.694	3.31	3.20	0.23	3.52
63	53.1	73.1	19.6	2.313	3.70	3.53	0.28	4.51
64	51.2	86.4	25.5	2.933	4.52	4.28	0.34	6.15
65	51.0	92.0	28.8	3.283	4.89	4.56	0.39	6.43
66	52.9	100.3	25.2	2.911	5.56	4.83	0.55	7.00
67	54.1	107.8	19.2	2.246	5.88	4.94	0.60	7.25
68	53.1	115.3	14.4	1.742	5.97	5.01	0.67	8.90
69	NA	NA	NA	NA	NA	NA	NA	NA
70	60.6	52.3	11.0	1.342	1.78	2.21	0.19	2.37
71	57.2	68.4	16.2	1.944	2.02	2.68	0.23	2.98
72	55.1	86.2	21.3	2.513	2.67	2.76	0.29	3.02
73	54.8	110.2	25.8	2.967	3.05	3.01	0.35	3.22
74	54.1	133.4	26.8	3.055	3.44	3.31	0.41	3.15
75	53.1	153.6	23.3	2.680	3.78	4.03	0.46	3.42
76	54.9	159.0	19.8	2.317	4.06	4.85	0.51	3.56
77	54.4	174.7	14.2	1.690	5.61	5.02	0.59	4.00
78	61.5	26.9	8.3	1.021	1.43	2.13	0.11	3.44
79	59.1	32.8	8.1	0.923	1.44	2.21	0.12	2.84
80	52.3	60.5	22.5	2.700	4.14	3.12	0.24	4.98
81	50.7	67.8	24.5	2.793	4.26	3.53	0.30	4.75
82	49.7	75.2	26.8	3.216	5.12	5.67	0.40	8.91
83	52.3	80.3	25.4	3.048	5.20	6.02	0.37	8.74
84	55.6	45.4	9.2	1.067	0.84	1.04	0.12	1.03
85	56.3	41.4	9.2	1.058	0.89	1.04	0.11	1.05
86	NA	NA	NA	NA	NA	NA	NA	NA
87	52.2	112.8	25.9	2.901	0.96	1.03	0.31	1.04
88	53.2	130.9	26.4	3.010	1.57	1.84	0.49	1.56
89	51.7	133.3	27.3	3.030	1.58	1.92	0.43	1.25

	I	J	K	L	M	N	O	P
90	46.2	83.5	21.5	2.537	1.69	1.89	0.33	3.58
91	49.4	82.3	20.6	2.493	1.94	1.95	0.29	6.46
92	54.1	84.7	19.7	2.423	1.95	1.93	0.23	6.01
93	61.8	75.3	17.3	2.163	2.37	2.05	0.19	6.55
94	67.8	71.0	16.1	2.125	2.55	2.19	0.17	6.90
95	52.3	78.9	20.6	2.493	1.98	2.21	0.32	3.84
96	53.1	75.8	18.9	2.344	2.16	2.45	0.24	6.55
97	53.2	73.4	17.6	2.270	1.65	2.25	0.22	6.23
98	56.7	71.2	16.4	2.280	1.02	2.40	0.20	6.98
99	NA	NA	NA	NA	NA	NA	NA	NA
100	54.8	39.4	9.4	1.062	1.43	1.98	0.12	2.69
101	53.2	60.1	11.4	1.277	1.59	2.23	0.20	4.62
102	52.8	73.9	18.9	1.984	1.97	2.69	0.25	5.03
103	51.9	104.6	23.9	2.390	2.04	2.90	0.37	7.78
104	51.1	104.2	26.4	2.534	2.87	3.12	0.42	8.80
105	50.1	140.3	32.9	2.994	3.01	3.14	0.47	9.03

	Q	R	S	T	U	V	W	X	Y	Z
1	Tar	Dust	T0	T1	T2	T3	T4	T5	T6	T7
2	content	content								
3	gas	gas								
4	(g/Nm3)	(g/Nm3)	(C)	(C)	(C)	(C)	(C)	(C)	(C)	(C)
5	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
6	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
7	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
8	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
10	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
11	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
12	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
13	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
14	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
15	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
16	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
17	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
18	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
19	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
20	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
21	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
22	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
23	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
24	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
25	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
26	NA	NA	35.4	682.0	571.1	233.1	143.9	107.2	95.1	39.1
27	NA	NA	34.9	700.0	594.5	237.0	145.8	108.6	96.1	40.6
28	NA	NA	34.8	768.6	636.8	240.1	148.1	113.2	98.6	41.0
29	NA	NA	32.7	817.6	644.3	244.4	150.0	118.0	101.0	44.3
30	NA	NA	32.9	832.8	663.2	267.7	154.0	123.3	103.8	45.8
31	NA	NA	33.4	853.3	670.8	278.1	157.2	125.3	105.2	47.8
32	NA	NA	34.0	879.3	709.1	281.2	160.9	127.7	109.1	49.7
33	NA	NA	34.3	929.9	718.8	290.2	164.2	129.7	113.5	51.3
34	NA	NA	32.8	691.2	575.7	200.9	142.0	105.9	92.6	38.7
35	NA	NA	33.4	725.7	590.1	217.7	143.5	109.6	95.4	40.0
36	NA	NA	33.8	780.6	650.8	230.1	149.5	115.7	99.5	43.8
37	NA	NA	34.4	826.3	680.2	278.4	150.4	118.0	101.7	45.1
38	NA	NA	32.6	876.0	695.5	285.8	154.6	120.0	103.0	45.5
39	NA	NA	34.3	895.9	700.6	288.3	156.2	125.1	106.5	45.9
40	NA	NA	33.5	947.7	715.7	289.4	157.9	126.3	108.2	46.4
41	NA	NA	34.5	970.6	727.5	296.9	158.8	128.2	112.3	47.4
42	NA	NA	33.5	981.8	745.5	306.0	160.3	130.8	114.0	48.3
43	NA	NA	32.6	693.7	584.4	212.6	145.0	108.8	97.6	40.0
44	NA	NA	33.3	725.8	600.5	231.5	148.6	110.5	98.6	42.6
45	NA	NA	32.9	765.7	625.5	250.8	151.6	114.7	99.4	44.5

	Q	R	S	T	U	V	W	X	Y	Z
46	NA	NA	34.4	825.6	675.4	275.5	153.1	118.3	103.2	46.3
47	NA	NA	31.2	894.5	704.7	282.6	155.0	121.5	105.1	47.0
48	NA	NA	33.9	905.3	740.0	298.4	158.3	123.8	107.1	49.0
49	NA	NA	35.4	925.4	785.2	315.4	161.3	128.8	110.8	49.5
50	NA	NA	33.3	965.9	790.2	325.6	173.5	130.2	112.5	50.2
51	NA	NA	34.0	985.4	795.5	340.3	178.2	131.4	116.1	51.5
52	NA	NA	31.4	705.2	590.0	235.4	146.8	109.6	97.5	40.8
53	NA	NA	33.1	735.1	615.2	245.1	149.7	111.7	99.3	41.6
54	NA	NA	33.8	789.8	645.8	265.3	152.5	113.7	102.3	43.6
55	NA	NA	34.6	840.3	690.7	280.5	153.2	119.1	105.7	45.6
56	NA	NA	33.3	875.4	715.2	291.9	155.5	121.9	106.0	46.0
57	NA	NA	34.8	900.8	744.9	298.7	156.2	123.2	107.7	47.2
58	NA	NA	32.6	924.8	790.3	315.6	158.6	125.1	108.4	48.3
59	NA	NA	33.9	955.5	800.8	329.8	164.2	127.1	109.9	49.1
60	NA	NA	32.8	970.7	835.0	340.4	173.9	128.3	112.2	48.0
61	NA	NA	33.7	716.2	600.6	255.7	151.4	112.7	102.0	42.7
62	NA	NA	32.6	791.4	635.5	288.8	154.8	119.2	103.7	43.7
63	NA	NA	34.0	860.7	695.9	295.3	156.7	123.5	105.3	44.9
64	NA	NA	34.7	895.1	725.4	305.1	157.0	125.9	108.2	46.1
65	NA	NA	35.3	940.2	790.6	315.4	158.9	126.2	110.4	46.7
66	NA	NA	33.5	975.2	840.6	335.1	163.6	127.5	112.5	48.3
67	NA	NA	34.1	990.8	880.9	345.1	169.1	128.3	113.2	49.2
68	NA	NA	34.5	1005.4	895.4	350.5	174.8	129.3	116.2	50.3
69	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
70	NA	NA	34.0	755.6	625.5	280.3	150.5	109.3	102.6	42.2
71	NA	NA	35.7	865.1	715.7	295.4	155.6	115.4	103.2	43.7
72	NA	NA	34.8	884.8	745.1	300.7	156.1	119.2	104.0	44.0
73	NA	NA	35.9	910.4	760.9	310.5	158.6	124.3	105.2	44.2
74	NA	NA	33.0	950.8	795.9	320.1	160.6	125.3	108.1	45.9
75	NA	NA	34.7	985.2	850.0	335.6	164.9	126.0	110.2	46.4
76	NA	NA	35.2	991.4	903.9	340.5	169.5	128.0	111.0	48.5
77	NA	NA	33.3	1005.2	915.2	348.7	175.4	129.8	112.8	48.9
78	1.360	0.082	33.0	790.8	643.5	278.4	152.8	116.6	105.9	43.9
79	1.450	0.064	36.9	766.5	641.3	260.7	155.8	120.2	107.5	44.6
80	1.330	0.071	33.4	894.6	724.1	300.8	165.2	129.1	111.1	45.1
81	1.260	0.053	33.7	911.7	733.1	314.7	160.9	126.0	110.4	48.0
82	1.230	0.050	34.3	925.1	730.7	320.3	164.4	129.4	113.1	48.8
83	1.100	0.044	33.9	920.8	727.3	325.4	169.4	129.3	114.5	49.3
84	1.150	0.061	33.7	775.3	615.0	232.3	144.4	105.0	96.5	44.1
85	1.170	0.042	34.0	710.2	640.1	241.4	138.8	106.5	90.8	45.0
86	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
87	1.000	0.030	33.5	927.9	725.0	316.0	165.2	128.6	110.5	48.4
88	0.980	0.021	35.0	928.5	735.1	315.3	164.8	128.5	109.4	47.6
89	0.980	0.025	35.4	931.7	786.7	320.8	168.2	130.4	113.1	48.0

	Q	R	S	T	U	V	W	X	Y	Z
90	1.150	0.030	33.5	825.2	634.0	227.9	142.8	113.2	93.9	43.7
91	1.210	0.032	33.6	798.7	600.2	212.0	138.6	108.5	91.8	42.6
92	1.230	0.043	34.0	720.2	595.9	218.2	132.4	101.2	89.9	41.9
93	1.241	0.042	33.8	700.7	574.5	204.4	129.3	98.6	85.6	40.3
94	1.320	0.044	35.0	680.0	554.6	203.9	125.9	96.0	81.4	40.6
95	1.360	0.080	32.6	836.7	636.5	225.3	144.8	112.2	93.4	43.3
96	1.340	0.073	33.1	799.1	606.7	218.0	137.8	107.7	90.8	41.4
97	1.600	0.091	33.5	786.3	596.4	209.5	131.1	103.2	88.9	40.8
98	1.670	0.101	33.6	714.3	592.0	205.3	127.2	98.6	84.8	40.4
99	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
100	1.130	0.023	33.0	784.7	647.0	256.1	149.6	113.2	100.5	45.9
101	1.010	0.022	33.6	825.2	654.3	269.7	152.0	118.3	104.8	44.5
102	0.990	0.022	34.6	842.1	702.4	299.9	157.1	124.3	108.2	45.9
103	0.980	0.022	35.8	899.2	714.9	311.4	159.5	125.4	106.7	47.1
104	0.950	0.020	35.8	985.1	796.7	319.4	160.4	127.6	110.5	47.4
105	0.951	0.018	36.0	1004.7	840.9	336.3	163.6	127.9	112.5	49.3

	AA	AB	AC	AD	AE
1	T8	Pgas	Pfil	Pcool	Psys
2					
3					
4	(C)	(mmWg)	(mmWg)	(mmWg)	(mmWg)
5	NA	NA	NA	NA	NA
6	NA	NA	NA	NA	NA
7	NA	NA	NA	NA	NA
8	NA	NA	NA	NA	NA
9	NA	NA	NA	NA	NA
10	NA	NA	NA	NA	NA
11	NA	NA	NA	NA	NA
12	NA	NA	NA	NA	NA
13	NA	NA	NA	NA	NA
14	NA	NA	NA	NA	NA
15	NA	NA	NA	NA	NA
16	NA	NA	NA	NA	NA
17	NA	NA	NA	NA	NA
18	NA	NA	NA	NA	NA
19	NA	NA	NA	NA	NA
20	NA	NA	NA	NA	NA
21	NA	NA	NA	NA	NA
22	NA	NA	NA	NA	NA
23	NA	NA	NA	NA	NA
24	NA	NA	NA	NA	NA
25	NA	NA	NA	NA	NA
26	406.4	NA	NA	NA	106
27	409.3	NA	NA	NA	119
28	414.1	NA	NA	NA	127
29	417.8	NA	NA	NA	134
30	435.9	NA	NA	NA	144
31	474.5	NA	NA	NA	150
32	480.0	NA	NA	NA	163
33	505.5	NA	NA	NA	173
34	392.5	NA	NA	NA	104
35	398.2	NA	NA	NA	112
36	418.5	NA	NA	NA	125
37	466.7	NA	NA	NA	131
38	488.9	NA	NA	NA	143
39	504.3	NA	NA	NA	153
40	507.1	NA	NA	NA	158
41	507.7	NA	NA	NA	162
42	509.5	NA	NA	NA	168
43	419.9	NA	NA	NA	102
44	424.2	NA	NA	NA	110
45	432.8	NA	NA	NA	113

	AA	AB	AC	AD	AE
46	441.4	NA	NA	NA	120
47	463.6	NA	NA	NA	129
48	469.9	NA	NA	NA	135
49	483.8	NA	NA	NA	146
50	495.4	NA	NA	NA	153
51	501.7	NA	NA	NA	163
52	409.5	NA	NA	NA	98
53	411.0	NA	NA	NA	103
54	440.3	NA	NA	NA	110
55	463.4	NA	NA	NA	114
56	475.8	NA	NA	NA	121
57	489.2	NA	NA	NA	128
58	493.3	NA	NA	NA	133
59	503.8	NA	NA	NA	140
60	504.1	NA	NA	NA	152
61	416.7	NA	NA	NA	96
62	443.5	NA	NA	NA	100
63	448.4	NA	NA	NA	106
64	460.1	NA	NA	NA	110
65	485.1	NA	NA	NA	115
66	496.5	NA	NA	NA	122
67	506.7	NA	NA	NA	130
68	507.8	NA	NA	NA	134
69	NA	NA	NA	NA	NA
70	443.8	NA	NA	NA	98
71	451.4	NA	NA	NA	101
72	464.3	NA	NA	NA	107
73	474.0	NA	NA	NA	113
74	489.8	NA	NA	NA	120
75	492.9	NA	NA	NA	126
76	501.0	NA	NA	NA	129
77	507.6	NA	NA	NA	137
78	439.9	27	47	26	100
79	458.9	32	61	27	120
80	478.6	36	62	29	126
81	490.2	43	71	32	146
82	507.1	44	72	33	148
83	509.6	59	75	36	170
84	467.4	28	55	23	105
85	478.4	32	60	23	116
86	NA	NA	NA	NA	NA
87	509.3	40	68	25	133
88	504.3	44	69	27	140
89	507.0	50	75	30	156

	AA	AB	AC	AD	AE
90	461.6	38	64	29	131
91	433.7	47	77	30	153
92	421.3	51	84	31	166
93	408.6	54	93	31	178
94	403.6	58	103	36	197
95	440.4	35	63	30	128
96	428.1	41	71	30	142
97	413.4	47	73	31	152
98	407.0	50	80	32	162
99	NA	NA	NA	NA	NA
100	429.3	38	55	24	117
101	433.5	44	62	24	130
102	445.8	48	64	26	138
103	458.5	51	67	27	145
104	497.2	55	71	29	155
105	499.1	61	73	33	167

APPENDIX IV

Mass balance, elemental balance, water balance, air-fuel ratio, specific gasification rate , turndown and equivalent ratio data for runs 22-101

	A	B	C	D	E	F	G	H	I
1	Run	Moisture	Wood	CO2	H2	CH4	CO	N2	Gas
2		content	used						flowrate
3		wet	wet						wet
4		(%)	(kg/h)	(%)	(%)	(%)	(%)	(%)	(Nm3/h)
5	R22	8.8	8.5	13.0	13.5	0.8	11.6	61.1	25.0
6	R23	9.9	16.2	12.8	14.5	0.8	14.6	57.3	43.2
7	R24	8.9	26.2	12.6	15.5	0.7	16.9	54.3	73.0
8	R25	10.3	33.5	12.3	18.4	0.6	18.9	49.8	89.3
9	R26	9.8	35.7	12.2	17.8	0.4	21.9	47.7	97.5
10	R27	10.4	42.8	11.9	15.9	0.5	21.9	49.8	113.6
11	R28	10.7	48.6	10.5	17.2	0.6	22.4	49.3	115.4
12	R29	9.8	65.8	9.9	18.5	0.5	23.5	47.6	112.2
13	R30	9.8	10.3	12.4	15.5	0.8	16.5	54.8	24.7
14	R31	9.6	19.4	11.2	16.5	0.7	21.3	50.3	40.0
15	R32	10.3	27.2	10.8	16.3	0.7	23.0	49.2	59.7
16	R33	10.6	34.5	9.8	17.7	0.8	24.1	47.6	72.9
17	R34	10.8	39.7	9.3	16.9	0.7	23.9	49.2	88.9
18	R35	10.2	45.3	9.1	17.9	0.7	24.5	47.8	106.4
19	R36	8.9	49.4	8.9	18.5	0.9	24.8	46.9	112.2
20	R37	8.7	55.6	8.8	17.8	1.2	25.2	47.0	113.0
21	R38	9.3	65.3	8.6	18.5	1.1	25.7	46.1	120.0
22	R39	9.5	10.6	11.4	16.2	0.8	18.7	52.9	20.4
23	R40	8.9	20.7	9.0	16.5	0.9	20.6	53.0	43.2
24	R41	10.3	29.0	8.6	15.5	0.9	24.5	50.5	55.8
25	R42	9.6	35.3	8.5	16.7	1.2	26.7	46.9	69.8
26	R43	10.1	42.9	8.5	17.3	0.9	28.5	44.8	84.3
27	R44	10.2	50.7	8.1	17.4	1.4	29.2	43.9	104.6
28	R45	9.7	55.9	8.2	16.9	1.3	28.9	44.7	131.8
29	R46	10.5	65.5	7.9	16.9	1.3	29.7	44.2	140.1
30	R47	9.1	75.3	7.8	16.5	1.5	29.5	44.7	120.0
31	R48	8.2	16.0	11.5	16.7	0.9	15.3	55.6	25.7
32	R49	9.6	23.4	10.5	17.1	0.8	18.5	53.1	43.5
33	R50	10.0	25.4	9.5	16.9	1.1	20.8	51.7	52.8
34	R51	9.3	28.8	8.3	16.3	0.9	25.6	48.9	59.7
35	R52	9.1	35.5	7.9	16.7	1.4	27.8	46.2	80.3
36	R53	9.6	42.9	8.3	16.9	1.5	26.6	46.7	95.7
37	R54	9.4	52.5	8.5	17.1	1.8	26.1	46.5	106.4
38	R55	8.3	66.1	8.9	16.8	1.7	25.8	46.8	110.5
39	R56	10.2	72.4	9.1	16.9	1.3	25.1	47.6	113.5
40	R57	9.4	20.4	8.1	16.4	0.9	15.3	59.3	34.6
41	R58	8.6	29.5	8.5	16.5	1.1	16.3	57.6	55.6
42	R59	8.3	35.7	9.8	16.9	1.6	18.6	53.1	73.1
43	R60	9.4	43.7	9.2	17.3	1.8	20.5	51.2	86.4
44	R61	9.3	50.1	9.8	17.8	1.7	19.7	51.0	92.0
45	R62	9.2	70.2	9.6	17.1	1.9	18.5	52.9	100.3

	A	B	C	D	E	F	G	H	I
46	R63	8.8	76.8	10.2	16.5	1.8	17.4	54.1	107.8
47	R64	8.6	85.0	11.3	16.4	2.1	17.1	53.1	115.3
48	R65	NA	NA	NA	NA	NA	NA	NA	NA
49	R66	8.8	24.0	9.8	15.2	1.4	13.0	60.6	52.3
50	R67	9.8	32.6	11.5	15.6	1.8	13.9	57.2	68.4
51	R68	10.4	38.5	12.6	15.1	2.1	15.1	55.1	86.2
52	R69	9.3	45.7	13.2	15.1	2.1	14.8	54.8	110.2
53	R70	9.8	52.7	14.5	14.9	2.3	14.2	54.1	133.4
54	R71	9.9	59.8	15.9	14.8	2.5	13.7	53.1	153.6
55	R72	8.3	67.2	16.3	14.5	2.4	11.9	54.9	159.0
56	R73	9.6	75.8	16.8	14.6	2.6	11.6	54.4	174.7
57	R74	15.5	15.5	11.6	9.0	0.8	17.1	61.5	26.9
58	R75	16.4	17.4	12.7	10.4	0.7	17.1	59.1	32.8
59	R76	15.5	38.5	12.8	15.6	0.8	18.5	52.3	60.5
60	R77	17.5	42.3	13.2	16.3	0.7	19.1	50.7	67.8
61	R78	15.5	55.6	11.9	17.3	0.6	20.5	49.7	75.2
62	R79	16.0	54.6	10.2	15.6	0.6	21.3	52.3	80.3
63	R80	15.4	16.9	12.8	13.5	0.8	17.3	55.6	45.4
64	R81	16.5	15.6	11.9	12.6	0.9	18.3	56.3	41.4
65	R82	NA	NA	NA	NA	NA	NA	NA	NA
66	R83	16.8	43.5	15.2	11.4	0.7	20.5	52.2	112.8
67	R84	14.6	53.6	12.5	12.8	0.7	20.8	53.2	130.9
68	R85	15.6	58.9	11.8	14.5	0.8	21.2	51.7	133.3
69	R86	8.5	42.3	15.5	14.8	1.1	22.4	46.2	83.5
70	R87	18.9	41.8	15.4	15.5	1.2	18.5	49.4	82.3
71	R88	31.3	39.5	14.5	13.6	1.0	16.8	54.1	84.7
72	R89	43.6	38.9	12.1	12.5	1.3	12.3	61.8	75.3
73	R90	51.5	41.1	11.0	13.0	1.3	6.9	67.8	71.0
74	R91	9.2	42.3	13.5	12.7	1.0	20.5	52.3	78.9
75	R92	18.6	40.5	16.3	12.9	0.9	16.8	53.1	75.8
76	R93	31.6	38.5	20.7	10.6	0.9	14.6	53.2	73.4
77	R94	43.5	41.2	22.4	9.5	1.1	10.3	56.7	71.2
78	R95	NA	NA	NA	NA	NA	NA	NA	NA
79	R96	15.7	18.9	14.0	15.2	1.3	14.7	54.8	39.4
80	R97	16.4	28.9	13.5	16.5	1.1	15.7	53.2	60.1
81	R98	14.8	34.1	13.0	17.3	0.9	16.0	52.8	73.9
82	R99	15.9	50.3	12.5	17.8	1.0	16.8	51.9	104.6
83	R100	15.3	57.9	10.8	18.7	1.0	18.4	51.1	104.2
84	R101	14.9	63.4	9.9	18.9	1.1	20.0	50.1	140.3

	J	K	L	M	N	O	P
1	Total wood	Total wood	Total	Water	Pressure	Temp.	Vapour
2	input	input	dry ash	in wood	at outlet	at	pressure
3	dry	daf	input	input		outlet	
4	(kg/h)	(kg/h)	(kg/h)	(kg/h)	(mmHg)	(K)	(mmHg)
5	7.75	7.64	0.12	0.75	757	312.1	52.73
6	14.60	14.38	0.22	1.60	757	313.6	57.11
7	23.87	23.51	0.36	2.33	756	314.0	58.34
8	30.05	29.60	0.45	3.45	756	317.3	69.33
9	32.20	31.72	0.48	3.50	756	318.8	74.88
10	38.35	37.77	0.58	4.45	756	320.8	82.87
11	43.40	42.75	0.65	5.20	755	322.7	91.14
12	59.35	58.46	0.89	6.45	755	324.3	97.20
13	9.29	9.15	0.14	1.01	757	311.7	51.60
14	17.54	17.27	0.26	1.86	757	313.0	55.32
15	24.40	24.03	0.37	2.80	756	316.8	67.56
16	30.84	30.38	0.46	3.66	756	318.1	72.25
17	35.41	34.88	0.53	4.29	756	318.5	73.74
18	40.68	40.07	0.61	4.62	756	318.9	75.26
19	45.00	44.33	0.68	4.40	755	319.4	77.21
20	50.76	50.00	0.76	4.84	755	320.4	81.23
21	59.23	58.34	0.89	6.07	755	321.3	84.99
22	9.59	9.45	0.14	1.01	757	313.0	55.32
23	18.86	18.57	0.28	1.84	757	315.6	63.46
24	26.01	25.62	0.39	2.99	757	317.5	70.05
25	31.91	31.43	0.48	3.39	757	319.3	76.82
26	38.57	37.99	0.58	4.33	757	320.0	79.60
27	45.53	44.85	0.68	5.17	756	322.0	88.02
28	50.48	49.72	0.76	5.42	756	322.5	90.24
29	58.62	57.74	0.88	6.88	756	323.2	92.51
30	68.45	67.42	1.03	6.85	755	324.5	102.09
31	14.69	14.47	0.22	1.31	757	313.8	57.72
32	21.15	20.84	0.32	2.25	757	314.6	60.22
33	22.86	22.52	0.34	2.54	757	316.6	66.86
34	26.12	25.73	0.39	2.68	757	318.6	74.12
35	32.27	31.79	0.48	3.23	757	319.0	75.65
36	38.78	38.20	0.58	4.12	756	320.2	80.41
37	47.57	46.85	0.71	4.94	756	321.3	84.99
38	60.61	59.70	0.91	5.49	756	322.1	88.46
39	65.02	64.04	0.98	7.38	756	321.0	83.71
40	18.48	18.21	0.28	1.92	757	315.7	63.79
41	26.96	26.56	0.40	2.54	757	316.7	67.21
42	32.74	32.25	0.49	2.96	757	317.9	71.51
43	39.59	39.00	0.59	4.11	757	319.1	76.04
44	45.44	44.76	0.68	4.66	757	319.7	78.40
45	63.74	62.79	0.96	6.46	756	321.3	84.99

	J	K	L	M	N	O	P
46	70.04	68.99	1.05	6.76	756	322.2	88.90
47	77.69	76.52	1.17	7.31	756	323.3	92.51
48	NA	NA	NA	NA	NA	NA	NA
49	21.89	21.56	0.33	2.11	757	315.2	62.14
50	29.41	28.96	0.44	3.19	757	316.7	67.21
51	34.50	33.98	0.52	4.00	757	317.0	68.26
52	41.45	40.83	0.62	4.25	757	317.2	68.97
53	47.54	46.82	0.71	5.16	757	318.9	75.26
54	53.88	53.07	0.81	5.92	757	319.4	77.21
55	61.62	60.70	0.92	5.58	756	321.5	85.85
56	68.52	67.50	1.03	7.28	756	321.9	87.58
57	13.10	12.90	0.20	2.40	757	316.9	67.91
58	14.55	14.33	0.22	2.85	757	317.6	70.41
59	32.53	32.04	0.49	5.97	756	318.1	72.25
60	34.90	34.37	0.52	7.40	756	321.0	83.71
61	46.98	46.28	0.70	8.62	756	321.8	87.14
62	45.86	45.18	0.69	8.74	755	322.3	89.34
63	14.30	14.08	0.21	2.60	757	317.1	68.61
64	13.03	12.83	0.20	2.57	757	318.0	71.88
65	NA	NA	NA	NA	NA	NA	NA
66	36.19	35.65	0.54	7.31	756	321.4	85.42
67	45.77	45.09	0.69	7.83	756	320.6	82.05
68	49.71	48.97	0.75	9.19	756	321.0	83.71
69	38.70	38.12	0.58	3.60	756	316.7	67.21
70	33.90	33.39	0.51	7.90	756	315.6	63.46
71	27.14	26.73	0.41	12.36	755	314.9	61.18
72	21.94	21.61	0.33	16.96	755	313.3	56.21
73	19.93	19.63	0.30	21.17	754	313.6	57.11
74	38.41	37.83	0.58	3.89	756	316.3	65.82
75	32.97	32.47	0.49	7.53	756	314.4	59.58
76	26.33	25.94	0.40	12.17	756	313.8	57.72
77	23.28	22.93	0.35	17.92	755	313.4	56.51
78	NA	NA	NA	NA	NA	NA	NA
79	15.93	15.69	0.24	2.97	757	318.9	75.26
80	24.16	23.80	0.36	4.74	756	317.5	70.05
81	29.05	28.62	0.44	5.05	756	318.9	72.26
82	42.30	41.67	0.63	8.00	756	320.1	80.00
83	49.04	48.31	0.74	8.86	756	320.4	81.64
84	53.95	53.14	0.81	9.45	755	322.3	89.34

	Q	R	S	T	U	V
1	Moisture	Mol. wt	Mol. Wt	Mass flow	Mass flow	Volume
2	gas	gas	gas	gas	gas	gas flow
3		(dry)	(wet)	(wet)	(dry)	(dry)
4	(%)	(kg/mol)	(kg/mol)	(kg/h)	(kg/h)	(Nm3/h)
5	7.49	26.47	25.84	25.13	23.25	19.67
6	8.16	26.18	25.51	42.67	39.19	33.52
7	8.36	25.90	25.24	71.14	65.19	56.38
8	10.10	25.11	24.39	83.23	74.83	66.75
9	10.99	25.28	24.48	90.75	80.78	71.58
10	12.31	25.71	24.76	106.30	93.21	81.21
11	13.73	25.14	24.16	104.59	90.23	80.41
12	14.78	24.71	23.72	99.37	84.69	76.76
13	7.31	25.86	25.28	24.32	22.54	19.53
14	7.88	25.42	24.83	38.53	35.49	31.27
15	9.81	25.41	24.68	56.38	50.85	44.83
16	10.57	24.87	24.14	67.08	59.99	54.03
17	10.81	25.01	24.25	82.07	73.20	65.56
18	11.06	24.72	23.98	96.98	86.26	78.17
19	11.39	24.51	23.76	101.08	89.56	81.86
20	12.06	24.64	23.84	101.78	89.51	81.39
21	12.68	24.43	23.62	106.80	93.25	85.49
22	7.88	25.52	24.92	19.72	18.16	15.95
23	9.15	25.04	24.40	40.54	36.83	32.95
24	10.20	25.24	24.50	52.27	46.94	41.66
25	11.29	24.87	24.10	63.95	56.73	51.08
26	11.75	24.75	23.96	76.63	67.62	61.19
27	13.18	24.60	23.73	93.47	81.15	73.88
28	13.55	24.76	23.85	118.15	102.13	92.39
29	13.94	24.71	23.78	124.96	107.54	97.47
30	15.64	24.78	23.72	106.19	89.59	80.99
31	8.25	25.39	24.78	24.64	22.60	19.94
32	8.64	25.14	24.52	41.16	37.60	33.51
33	9.69	24.99	24.32	49.23	44.46	39.85
34	10.85	24.98	24.22	55.10	49.12	44.05
35	11.10	24.75	24.00	73.35	65.21	59.01
36	11.90	24.75	23.95	86.78	76.45	69.18
37	12.67	24.70	23.85	95.75	83.62	75.84
38	13.25	24.85	23.94	99.59	86.39	77.86
39	12.45	24.91	24.05	103.08	90.24	81.16
40	9.20	24.92	24.29	32.31	29.34	26.37
41	9.74	24.94	24.26	51.71	46.67	41.92
42	10.43	24.98	24.25	67.70	60.64	54.37
43	11.17	24.76	24.00	78.90	70.09	63.41
44	11.55	24.74	23.96	83.69	74.02	67.03
45	12.67	24.86	23.99	90.80	79.30	71.45

	Q	R	S	T	U	V
46	13.33	25.13	24.18	98.06	85.00	75.77
47	13.94	25.29	24.28	104.96	90.32	79.99
48	NA	NA	NA	NA	NA	NA
49	8.94	25.45	24.78	49.92	45.45	40.01
50	9.74	25.57	24.83	65.10	58.76	51.48
51	9.91	25.84	25.06	82.73	74.53	64.61
52	10.02	25.93	25.14	106.02	95.39	82.39
53	11.04	26.17	25.27	128.31	114.15	97.70
54	11.36	26.40	25.44	148.53	131.66	111.73
55	12.81	26.55	25.45	152.62	133.07	112.27
56	13.10	26.58	25.46	167.49	145.54	122.65
57	9.86	27.42	26.49	27.30	24.61	20.10
58	10.26	27.24	26.30	32.97	29.59	24.33
59	10.57	25.90	25.06	57.79	51.68	44.70
60	12.45	25.79	24.82	63.56	55.64	48.33
61	13.03	25.33	24.38	69.07	60.07	53.11
62	13.42	25.50	24.50	73.90	63.98	56.19
63	9.97	26.44	25.60	44.50	40.06	33.94
64	10.49	26.52	25.63	40.50	36.25	30.62
65	NA	NA	NA	NA	NA	NA
66	12.74	27.38	26.19	111.43	97.24	79.54
67	12.17	26.59	25.54	126.44	111.04	93.55
68	12.45	26.02	25.02	125.98	110.29	94.94
69	9.76	26.50	25.67	82.05	74.05	62.59
70	9.16	26.29	25.53	80.71	73.32	62.47
71	8.82	26.66	25.90	84.35	76.91	64.61
72	8.04	26.53	25.84	75.20	69.16	58.39
73	8.19	26.22	25.55	69.94	64.21	54.85
74	9.54	26.74	25.90	78.34	70.87	59.37
75	8.56	27.15	26.36	77.06	70.47	58.15
76	8.27	28.45	27.58	78.22	71.76	56.50
77	8.09	28.98	28.09	77.28	71.02	54.89
78	NA	NA	NA	NA	NA	NA
79	11.04	26.13	25.23	37.85	33.67	28.86
80	10.21	25.74	24.95	57.25	51.41	44.74
81	10.57	25.47	24.68	69.35	62.02	54.53
82	11.83	25.25	24.39	96.64	85.20	75.58
83	12.11	24.75	23.93	94.35	82.93	75.06
84	13.42	24.54	23.66	124.70	107.97	98.56

	W	X	Y	Z	AA	AB
1	Mass flow	Mass flow	Volume	Mass flow	Tar	Tar
2	water in	air	air flow	water in	content	content
3	gas	(dry)	(dry)	air	in gas	in gas
4	(kg/h)	(kg/h)	(Nm3/h)	(kg/h)	(g/Nm3)	(kg/h)
5	1.88	20.86	16.15	0.56	NA	NA
6	3.48	33.35	25.81	0.90	NA	NA
7	5.95	53.15	41.14	1.43	NA	NA
8	8.40	57.71	44.67	1.55	NA	NA
9	9.98	59.28	45.88	1.59	NA	NA
10	13.09	70.21	54.35	1.89	NA	NA
11	14.36	68.82	53.27	1.85	NA	NA
12	14.68	63.43	49.09	1.71	NA	NA
13	1.78	18.58	14.38	0.50	NA	NA
14	3.04	27.31	21.14	0.73	NA	NA
15	5.53	38.29	29.64	1.03	NA	NA
16	7.09	44.65	34.56	1.20	NA	NA
17	8.87	56.00	43.34	1.51	NA	NA
18	10.72	64.87	50.21	1.74	NA	NA
19	11.51	66.66	51.59	1.79	NA	NA
20	12.27	66.41	51.40	1.79	NA	NA
21	13.55	68.42	52.96	1.84	NA	NA
22	1.55	14.64	11.34	0.39	NA	NA
23	3.71	30.31	23.46	0.82	NA	NA
24	5.33	36.53	28.27	0.98	NA	NA
25	7.22	41.59	32.19	1.12	NA	NA
26	9.00	47.59	36.84	1.28	NA	NA
27	12.32	56.31	43.58	1.51	NA	NA
28	16.01	71.70	55.49	1.93	NA	NA
29	17.42	74.79	57.89	2.01	NA	NA
30	16.60	62.85	48.65	1.69	NA	NA
31	2.03	19.25	14.90	0.52	NA	NA
32	3.56	30.89	23.91	0.83	NA	NA
33	4.77	35.76	27.68	0.96	NA	NA
34	5.98	37.39	28.94	1.01	NA	NA
35	8.14	47.33	36.63	1.27	NA	NA
36	10.33	56.09	43.41	1.51	NA	NA
37	12.13	61.22	47.39	1.65	NA	NA
38	13.20	63.26	48.97	1.70	NA	NA
39	12.83	67.07	51.91	1.80	NA	NA
40	2.97	27.15	21.01	0.73	NA	NA
41	5.04	41.92	32.44	1.13	NA	NA
42	7.06	50.12	38.80	1.35	NA	NA
43	8.81	56.36	43.63	1.52	NA	NA
44	9.67	59.35	45.94	1.60	NA	NA
45	11.50	65.62	50.79	1.77	NA	NA

	W	X	Y	Z	AA	AB
46	13.07	71.17	55.08	1.91	NA	NA
47	14.63	73.74	57.08	1.98	NA	NA
48	NA	NA	NA	NA	NA	NA
49	4.46	42.09	32.58	1.13	NA	NA
50	6.34	51.12	39.57	1.38	NA	NA
51	8.20	61.81	47.84	1.66	NA	NA
52	10.63	78.39	60.67	2.11	NA	NA
53	14.17	91.77	71.03	2.47	NA	NA
54	16.87	103.00	79.72	2.77	NA	NA
55	19.55	107.00	82.82	2.88	NA	NA
56	21.95	115.84	89.66	3.12	NA	NA
57	2.69	21.46	16.61	0.58	1.36	0.03
58	3.38	24.96	19.32	0.67	1.45	0.04
59	6.11	40.59	31.42	1.09	1.33	0.06
60	7.91	42.54	32.92	1.14	1.26	0.06
61	9.00	45.83	35.47	1.23	1.23	0.07
62	9.92	51.02	39.49	1.37	1.10	0.06
63	4.43	32.76	25.35	0.88	1.15	0.04
64	4.25	29.93	23.16	0.81	1.17	0.04
65	NA	NA	NA	NA		
66	14.19	72.08	55.79	1.94	1.00	0.08
67	15.39	86.40	66.88	2.32	0.98	0.09
68	15.69	85.21	65.95	2.29	0.98	0.09
69	8.01	50.20	38.86	1.35	1.15	0.07
70	7.40	53.57	41.47	1.44	1.21	0.08
71	7.44	60.68	46.97	1.63	1.23	0.08
72	6.05	62.65	48.49	1.69	1.24	0.07
73	5.73	64.56	49.97	1.74	1.32	0.07
74	7.47	53.91	41.72	1.45	1.36	0.08
75	6.59	53.60	41.49	1.44	1.34	0.08
76	6.47	52.18	40.39	1.40	1.60	0.09
77	6.25	54.03	41.82	1.45	1.67	0.09
78	NA	NA	NA	NA		NA
79	4.18	27.46	21.25	0.74	1.13	0.03
80	5.85	41.32	31.98	1.11	1.01	0.05
81	7.33	49.99	38.69	1.34	0.99	0.05
82	11.44	68.10	52.71	1.83	0.98	0.07
83	11.42	66.59	51.54	1.79	0.95	0.07
84	16.74	85.72	66.35	2.31	0.95	0.09

	AC	AD	AE	AF	AG	AH
4	(kg/h)	(kg/h)	(kg/h)	(kg/h)	(kg/h)	(kg/h)
5	0.35	0.35	0.84	0.07	0.92	0.91
6	0.97	0.97	1.09	0.13	1.79	1.78
7	0.99	0.99	1.34	0.21	1.60	1.59
8	0.98	0.98	1.07	0.35	1.69	1.68
9	1.20	1.20	1.16	0.32	1.32	1.31
10	1.33	1.33	1.13	0.33	1.60	1.59
11	2.68	2.68	2.03	0.36	3.12	3.10
12	3.46	3.46	3.49	0.52	6.25	6.20
13	0.95	0.95	0.89	0.08	1.99	1.97
14	1.33	1.33	1.46	0.15	2.21	2.19
15	1.89	1.89	1.68	0.21	2.34	2.32
16	1.98	1.98	1.94	0.26	3.62	3.59
17	2.16	2.16	2.02	0.31	4.16	4.13
18	1.43	1.43	2.47	0.35	4.17	4.14
19	2.74	2.74	2.57	0.39	4.41	4.37
20	3.56	3.56	3.56	0.43	4.82	4.78
21	3.89	3.89	4.76	0.51	6.04	5.99
22	0.97	0.97	1.12	0.08	1.96	1.94
23	1.79	1.79	1.78	0.16	2.55	2.53
24	1.96	1.96	2.26	0.24	2.97	2.95
25	2.15	2.15	2.20	0.28	3.38	3.35
26	2.46	2.46	2.94	0.33	4.22	4.19
27	3.22	3.22	3.13	0.39	4.87	4.83
28	3.21	3.21	2.95	0.43	4.71	4.67
29	3.64	3.64	3.61	0.50	5.84	5.79
30	3.73	3.73	4.73	0.59	6.96	6.90
31	1.95	1.95	2.01	0.14	2.43	2.41
32	2.03	2.03	2.35	0.18	2.38	2.36
33	1.86	1.86	2.95	0.19	2.55	2.53
34	2.04	2.04	3.34	0.23	2.64	2.62
35	2.33	2.33	3.74	0.28	3.14	3.11
36	2.74	2.74	3.84	0.33	4.11	4.08
37	2.89	2.89	4.06	0.42	4.93	4.89
38	3.87	3.87	4.88	0.53	6.83	6.78
39	4.31	4.31	4.92	0.56	7.33	7.27
40	2.84	2.84	3.15	0.15	3.05	3.03
41	3.31	3.31	3.20	0.23	3.52	3.49
42	3.70	3.70	3.53	0.28	4.51	4.47
43	4.52	4.52	4.28	0.34	6.15	6.10
44	4.89	4.89	4.56	0.39	6.43	6.38
45	5.56	5.56	4.83	0.55	7.00	6.94

	AC	AD	AE	AF	AG	AH
46	5.88	5.88	4.94	0.60	7.25	7.19
47	5.97	5.97	5.01	0.67	8.90	8.83
48	NA	NA	NA	NA	NA	NA
49	1.78	1.78	2.21	0.19	2.37	2.35
50	2.02	2.02	2.68	0.23	2.98	2.96
51	2.67	2.67	2.76	0.29	3.02	3.00
52	3.05	3.05	3.01	0.35	3.22	3.19
53	3.44	3.44	3.31	0.41	3.15	3.12
54	3.78	3.78	4.03	0.46	3.42	3.39
55	4.06	4.06	4.85	0.51	3.56	3.53
56	5.61	5.61	5.02	0.59	4.00	3.97
57	1.43	1.46	2.13	0.11	3.44	3.41
58	1.44	1.48	2.21	0.12	2.84	2.82
59	4.14	4.20	3.12	0.24	4.98	4.94
60	4.26	4.32	3.53	0.30	4.75	4.71
61	5.12	5.19	5.67	0.40	8.91	8.84
62	5.20	5.26	6.02	0.37	8.74	8.67
63	0.84	0.88	1.04	0.12	1.03	1.02
64	0.89	0.93	1.04	0.11	1.05	1.04
65	NA	NA	NA	NA	NA	NA
66	0.96	1.04	1.03	0.31	1.04	1.03
67	1.57	1.66	1.84	0.49	1.56	1.55
68	1.58	1.67	1.92	0.43	1.25	1.24
69	1.69	1.76	1.89	0.33	3.58	3.55
70	1.94	2.02	1.95	0.29	6.46	6.41
71	1.95	2.03	1.93	0.23	6.01	5.96
72	2.37	2.44	2.05	0.19	6.55	6.50
73	2.55	2.62	2.19	0.17	6.90	6.84
74	1.98	2.06	2.21	0.32	3.84	3.81
75	2.16	2.24	2.45	0.24	6.55	6.50
76	1.65	1.74	2.25	0.22	6.23	6.18
77	1.02	1.11	2.40	0.20	6.98	6.92
78	NA	NA	NA	NA	NA	NA
79	1.43	1.46	1.98	0.12	2.69	2.67
80	1.59	1.64	2.23	0.20	4.62	4.58
81	1.97	2.02	2.69	0.25	5.03	4.99
82	2.04	2.11	2.90	0.37	7.78	7.72
83	2.87	2.94	3.12	0.42	8.80	8.73
84	3.01	3.10	3.14	0.47	9.03	8.96

	AI	AJ	AK	AL	AM	AN	AO
1	Total	Total	Total	Total	Mass	Total	Total
2	O2 input	N2 input	mass	mass	Balance	C	O
3	dry	dry	input	output	closure	input	input
4	(kg/h)	(kg/h)	(kg/h)	(kg/h)	(%)	(kg/h)	(kg/h)
5	5.28	15.02	29.36	27.31	**93.00**	3.76	9.39
6	8.44	24.01	49.55	46.65	**94.14**	7.07	16.36
7	13.45	38.27	79.35	75.28	**94.88**	11.57	26.14
8	14.61	41.55	91.21	87.32	**95.74**	14.56	31.03
9	15.00	42.68	94.98	94.75	**99.76**	15.61	32.43
10	17.77	50.56	113.02	110.69	**97.94**	18.58	38.78
11	17.42	49.55	117.42	112.78	**96.05**	21.03	41.34
12	16.05	45.67	129.23	113.09	**87.51**	28.76	48.19
13	4.70	13.38	28.88	28.23	**97.76**	4.50	9.73
14	6.91	19.66	46.71	43.68	**93.50**	8.50	16.37
15	9.69	27.57	65.50	62.50	**95.43**	11.82	23.03
16	11.30	32.15	79.15	74.88	**94.60**	14.95	28.27
17	14.17	40.32	95.70	90.72	**94.80**	17.16	33.73
18	16.42	46.71	110.17	105.40	**95.67**	19.71	38.62
19	16.87	47.99	116.06	111.19	**95.80**	21.81	40.80
20	16.81	47.82	122.01	114.15	**93.56**	24.60	43.69
21	17.32	49.26	133.72	122.00	**91.23**	28.70	49.06
22	3.71	10.54	25.25	23.85	**94.47**	4.65	8.87
23	7.67	21.83	51.01	46.82	**91.78**	9.14	17.70
24	9.24	26.30	65.53	59.70	**91.11**	12.61	23.47
25	10.53	29.95	76.89	71.96	**93.58**	15.46	27.74
26	12.05	34.27	90.49	86.58	**95.67**	18.69	33.05
27	14.25	40.54	107.01	105.08	**98.20**	22.06	39.10
28	18.15	51.62	127.60	129.45	**101.45**	24.46	45.42
29	18.93	53.85	140.29	138.55	**98.76**	28.41	51.12
30	15.91	45.25	138.15	122.20	**88.46**	33.17	52.45
31	4.87	13.86	35.25	31.17	**88.42**	7.12	12.57
32	7.82	22.24	54.29	48.10	**88.60**	10.25	19.22
33	9.05	25.75	61.16	56.78	**92.83**	11.08	21.48
34	9.46	26.92	66.19	63.35	**95.71**	12.66	23.46
35	11.98	34.08	82.83	82.84	**100.02**	15.64	29.20
36	14.20	40.39	98.99	97.80	**98.80**	18.79	35.11
37	15.50	44.08	113.73	108.05	**95.01**	23.05	41.04
38	16.01	45.55	129.37	115.70	**89.43**	29.37	47.86
39	16.98	48.29	139.47	120.20	**86.18**	31.51	52.47
40	6.87	19.55	47.55	41.50	**87.29**	8.96	16.80
41	10.61	30.18	71.42	61.97	**86.77**	13.07	24.86
42	12.69	36.09	85.82	79.72	**92.89**	15.86	29.88
43	14.27	40.58	100.07	94.19	**94.13**	19.19	35.53
44	15.02	42.73	109.45	99.96	**91.33**	22.02	39.38
45	16.61	47.25	135.82	108.74	**80.07**	30.89	50.71

	AI	AJ	AK	AL	AM	AN	AO
46	18.01	51.24	147.97	116.73	**78.89**	33.94	55.18
47	18.66	53.10	158.75	125.51	**79.06**	37.65	59.73
48	NA	NA	NA	NA	**NA**	NA	NA
49	10.65	30.31	66.09	56.47	**85.44**	10.61	22.26
50	12.94	36.81	83.72	73.01	**87.21**	14.25	28.86
51	15.64	44.50	100.31	91.47	**91.19**	16.72	34.54
52	19.84	56.44	124.09	115.65	**93.20**	20.09	42.05
53	23.23	66.07	144.47	138.62	**95.96**	23.04	48.95
54	26.07	74.16	162.80	160.22	**98.42**	26.11	55.29
55	27.08	77.04	174.21	165.60	**95.06**	29.86	59.44
56	29.32	83.41	191.64	182.71	**95.34**	33.21	66.26
57	5.43	15.45	36.96	34.44	**93.16**	6.35	13.39
58	6.32	17.97	42.36	39.61	**93.52**	7.05	15.32
59	10.27	29.23	79.09	70.33	**88.92**	15.77	30.05
60	10.77	30.63	84.84	76.46	**90.12**	16.91	32.87
61	11.60	33.00	101.43	89.23	**87.98**	22.77	40.16
62	12.91	36.74	105.62	94.29	**89.27**	22.23	41.08
63	8.29	23.59	49.66	47.56	**95.78**	6.93	16.96
64	7.57	21.55	45.53	43.63	**95.82**	6.31	15.65
65	NA	NA	NA	NA	**NA**	NA	NA
66	18.24	51.90	115.58	114.85	**99.37**	17.54	40.83
67	21.87	62.21	140.00	131.99	**94.27**	22.18	49.18
68	21.57	61.36	144.12	131.25	**91.07**	24.09	51.84
69	12.71	36.15	92.50	89.62	**96.88**	18.76	33.12
70	13.56	38.57	95.38	91.43	**95.86**	16.43	35.66
71	15.36	43.69	100.18	94.55	**94.37**	13.15	38.41
72	15.86	45.11	101.55	86.44	**85.12**	10.63	40.68
73	16.34	46.48	105.66	81.83	**77.44**	9.66	44.01
74	13.64	38.81	96.21	86.77	**90.19**	18.61	34.19
75	13.57	38.59	94.10	88.54	**94.08**	15.98	34.92
76	13.21	37.57	90.69	88.66	**97.77**	12.76	35.73
77	13.68	38.91	95.24	87.97	**92.37**	11.28	39.95
78	NA	NA	NA	NA	**NA**	NA	NA
79	6.95	19.77	46.36	44.10	**95.13**	7.72	16.67
80	10.46	29.75	70.22	65.94	**93.90**	11.71	25.42
81	12.65	35.99	84.09	79.34	**94.35**	14.08	30.06
82	17.24	49.03	118.40	109.80	**92.74**	20.50	43.16
83	16.85	47.95	124.49	109.63	**88.06**	23.77	46.54
84	21.70	61.72	149.13	140.45	**94.18**	26.15	54.09

	AP	AQ	AR	AS	AT	AU	AV	AW
1	Total	Mass	Mass	Mass	Mass	Mass	Total	Closure
2	H	flow	flow	flow	flow	flow	C	C
3	input	H2	CO	CO2	CH4	N2	output	
4	(kg/h)	(kg/h)	(kg/h)	(kg/h)	(kg/h)	(kg/h)	(kg/h)	(%)
5	0.57	0.24	2.85	5.02	0.11	15.02	3.75	**99.74**
6	1.08	0.43	6.12	8.43	0.19	24.01	6.84	**96.70**
7	1.73	0.78	11.91	13.95	0.28	38.27	11.15	**96.42**
8	2.21	1.10	15.77	16.13	0.29	41.55	13.13	**90.19**
9	2.34	1.14	19.60	17.15	0.20	42.68	15.25	**97.69**
10	2.82	1.15	22.23	18.98	0.29	50.56	17.01	**91.51**
11	3.18	1.23	22.51	16.58	0.34	49.55	18.39	**87.44**
12	4.18	1.27	22.55	14.93	0.27	45.67	19.89	**69.15**
13	0.68	0.27	4.03	4.76	0.11	13.38	4.67	**103.83**
14	1.26	0.46	8.33	6.88	0.16	19.66	7.96	**93.70**
15	1.77	0.65	12.89	9.51	0.22	27.57	11.32	**95.72**
16	2.24	0.85	16.28	10.40	0.31	32.15	13.39	**89.61**
17	2.60	0.99	19.59	11.98	0.33	40.32	15.47	**90.13**
18	2.95	1.25	23.94	13.97	0.39	46.71	17.81	**90.35**
19	3.17	1.35	25.38	14.31	0.53	47.99	19.70	**90.32**
20	3.54	1.29	25.64	14.07	0.70	47.82	21.44	**87.15**
21	4.15	1.41	27.46	14.44	0.67	49.26	23.71	**82.59**
22	0.68	0.23	3.73	3.57	0.09	10.54	4.44	**95.59**
23	1.34	0.49	8.48	5.82	0.21	21.83	8.44	**92.31**
24	1.88	0.58	12.76	7.04	0.27	26.30	11.23	**89.09**
25	2.26	0.76	17.05	8.53	0.44	29.95	13.69	**88.51**
26	2.75	0.95	21.80	10.22	0.39	34.27	17.10	**91.47**
27	3.25	1.15	26.97	11.76	0.74	40.54	20.74	**94.00**
28	3.60	1.39	33.38	14.88	0.86	51.62	24.25	**99.12**
29	4.22	1.47	36.18	15.12	0.91	53.85	26.51	**93.32**
30	4.72	1.19	29.87	12.41	0.87	45.25	24.18	**72.89**
31	1.01	0.30	3.81	4.50	0.13	13.86	6.35	**89.26**
32	1.51	0.51	7.75	6.91	0.19	22.24	9.13	**89.07**
33	1.65	0.60	10.36	7.44	0.31	25.75	10.93	**98.70**
34	1.85	0.64	14.09	7.18	0.28	26.92	12.95	**102.33**
35	2.28	0.88	20.50	9.16	0.59	34.08	17.07	**109.17**
36	2.76	1.04	23.00	11.28	0.74	40.39	19.24	**102.36**
37	3.36	1.16	24.74	12.66	0.98	44.08	20.86	**90.50**
38	4.14	1.17	25.11	13.61	0.95	45.55	22.78	**77.54**
39	4.61	1.22	25.46	14.51	0.75	48.29	23.40	**74.26**
40	1.31	0.39	5.04	4.20	0.17	19.55	8.59	**95.91**
41	1.89	0.62	8.54	7.00	0.33	30.18	11.37	**87.04**
42	2.28	0.82	12.64	10.47	0.62	36.09	14.91	**93.95**
43	2.81	0.98	16.25	11.46	0.82	40.58	18.20	**94.87**
44	3.20	1.07	16.51	12.90	0.81	42.73	19.25	**87.43**
45	4.43	1.09	16.52	13.47	0.97	47.25	20.29	**65.69**

	AP	AQ	AR	AS	AT	AU	AV	AW
46	4.83	1.12	16.48	15.18	0.97	51.24	21.09	62.13
47	5.32	1.17	17.10	17.76	1.20	53.10	22.36	59.39
48	NA	NA	NA	NA	NA	NA	NA	NA
49	1.57	0.54	6.50	7.70	0.40	30.31	8.65	81.52
50	2.13	0.72	8.94	11.63	0.66	36.81	11.59	81.35
51	2.53	0.87	12.20	15.99	0.97	44.50	14.97	89.55
52	2.99	1.11	15.24	21.36	1.24	56.44	18.47	91.93
53	3.47	1.30	17.34	27.83	1.61	66.07	21.99	95.44
54	3.94	1.48	19.13	34.90	2.00	74.16	25.92	99.27
55	4.34	1.45	16.70	35.95	1.92	77.04	26.11	87.44
56	4.93	1.60	17.79	40.48	2.28	83.41	29.40	88.53
57	1.05	0.16	4.30	4.58	0.11	15.45	6.32	99.54
58	1.19	0.23	5.20	6.07	0.12	17.97	7.21	102.23
59	2.58	0.62	10.34	11.24	0.26	29.23	13.83	87.74
60	2.87	0.70	11.54	12.53	0.24	30.63	15.18	89.73
61	3.69	0.82	13.61	12.41	0.23	33.00	18.73	82.26
62	3.65	0.78	14.96	11.26	0.24	36.74	19.40	87.26
63	1.18	0.41	7.34	8.53	0.19	23.59	7.28	105.02
64	1.09	0.34	7.00	7.16	0.20	21.55	6.80	107.65
65	NA	NA	NA	NA	NA	NA	NA	NA
66	3.02	0.81	20.38	23.75	0.40	51.90	17.28	98.52
67	3.65	1.07	24.32	22.97	0.47	62.21	20.05	90.40
68	4.02	1.23	25.16	22.01	0.54	61.36	20.29	84.23
69	2.68	0.83	17.53	19.06	0.49	36.15	16.22	86.45
70	2.91	0.86	14.45	18.90	0.54	38.57	15.13	92.11
71	3.05	0.78	13.57	18.40	0.46	43.69	14.56	110.69
72	3.28	0.65	8.98	13.88	0.54	45.11	11.84	111.36
73	3.64	0.64	4.73	11.85	0.51	46.48	9.71	100.54
74	2.71	0.67	15.21	15.74	0.42	38.81	14.80	79.52
75	2.82	0.67	12.21	18.62	0.37	38.59	14.62	91.54
76	2.96	0.53	10.31	22.97	0.36	37.57	14.43	113.04
77	3.44	0.47	7.07	24.15	0.43	38.91	13.08	115.97
78	NA	NA	NA	NA	NA	NA	NA	NA
79	1.29	0.39	5.30	7.94	0.27	19.77	7.64	98.94
80	1.98	0.66	8.78	11.86	0.35	29.75	10.63	90.81
81	2.31	0.84	10.91	13.93	0.35	35.99	12.84	91.19
82	3.43	1.20	15.87	18.56	0.54	49.03	16.64	81.18
83	3.89	1.25	17.26	15.92	0.54	47.95	17.35	73.00
84	4.28	1.66	24.64	19.17	0.77	61.72	21.71	83.04

	AX	AY	AZ	BA	BB	BC	BD	BE
1	Total	Closure	Total	Closure	Closure	Total	Total	Closure
2	O	O	H	H	nitrogen	water	water	water
3	output		output			input	output	
4	(kg/h)	(kg/h)	(kg/h)	(kg/h)	(%)	(kg/h)	(kg/h)	(%)
5	7.85	83.56	0.62	107.70	100.00	1.31	2.79	213.41
6	14.49	88.61	1.17	107.70	100.00	2.50	5.26	210.22
7	23.85	91.27	1.79	103.39	100.00	3.76	7.54	200.36
8	29.89	96.32	2.39	107.94	100.00	5.00	10.08	201.49
9	33.94	104.65	2.56	109.51	100.00	5.09	11.29	221.60
10	39.81	102.65	2.99	106.01	100.00	6.34	14.67	231.46
11	40.95	99.04	3.53	110.97	100.00	7.05	17.45	247.52
12	42.98	89.18	4.01	95.94	100.00	8.15	20.88	256.09
13	9.28	95.38	0.81	119.29	100.00	1.51	3.75	248.70
14	14.67	89.65	1.22	96.99	100.00	2.60	5.23	201.37
15	21.63	93.89	1.77	100.00	100.00	3.83	7.85	204.99
16	26.74	94.60	2.32	103.49	100.00	4.86	10.68	219.82
17	31.87	94.48	2.73	105.27	100.00	5.79	13.00	224.32
18	37.35	96.73	3.16	106.95	100.00	6.37	14.86	233.42
19	39.56	96.98	3.53	111.25	100.00	6.19	15.89	256.70
20	40.73	93.23	3.73	105.36	100.00	6.62	17.05	257.45
21	44.34	90.38	4.16	100.29	100.00	7.91	19.54	246.91
22	8.03	90.55	0.74	108.49	100.00	1.40	3.50	249.76
23	14.98	84.64	1.41	105.88	100.00	2.66	6.24	234.76
24	20.16	85.88	1.77	94.17	100.00	3.97	8.28	208.50
25	25.77	92.90	2.27	100.22	100.00	4.51	10.58	234.61
26	32.10	97.12	2.77	100.54	100.00	5.61	13.19	234.99
27	39.83	101.85	3.57	109.55	100.00	6.69	17.15	256.47
28	48.90	107.67	4.23	117.50	100.00	7.35	20.69	281.41
29	53.02	103.72	4.65	110.10	100.00	8.89	23.22	261.17
30	47.74	91.01	4.41	93.44	100.00	8.54	23.51	275.19
31	9.79	77.85	1.02	100.92	100.00	1.83	4.44	242.88
32	15.12	78.64	1.43	94.64	100.00	3.08	5.92	192.32
33	18.21	84.77	1.69	102.62	100.00	3.50	7.30	208.42
34	21.35	91.00	1.89	102.21	100.00	3.68	8.60	233.42
35	28.87	98.87	2.53	111.08	100.00	4.50	11.26	250.00
36	34.71	98.88	3.12	112.96	100.00	5.63	14.41	256.01
37	39.07	95.19	3.60	107.35	100.00	6.58	17.02	258.56
38	42.78	89.40	4.03	97.30	100.00	7.19	19.97	277.85
39	43.83	83.54	4.09	88.86	100.00	9.19	20.11	218.81
40	11.83	70.42	1.39	105.69	100.00	2.65	6.00	226.57
41	18.20	73.20	1.98	104.73	100.00	3.66	8.53	232.77
42	25.81	86.37	2.63	115.24	100.00	4.31	11.54	267.58
43	31.75	89.36	3.30	117.43	100.00	5.62	14.91	265.13
44	34.03	86.41	3.55	110.78	100.00	6.26	16.05	256.53
45	36.70	72.38	3.94	88.97	100.00	8.22	18.45	224.30

	AX	AY	AZ	BA	BB	BC	BD	BE
46	39.59	71.75	4.20	87.00	100.00	8.67	20.26	233.61
47	44.68	74.80	4.68	87.92	100.00	9.29	23.46	252.46
48	NA	NA	NA	NA	NA	NA	NA	NA
49	15.73	70.66	1.59	101.22	100.00	3.24	6.82	210.07
50	22.24	77.09	2.13	100.00	100.00	4.57	9.30	203.49
51	29.07	84.17	2.63	103.88	100.00	5.67	11.19	197.56
52	37.13	88.30	3.27	109.13	100.00	6.36	13.82	217.37
53	46.19	94.35	3.97	114.45	100.00	7.63	17.29	226.51
54	55.07	99.60	4.62	117.21	100.00	8.69	20.26	233.15
55	57.02	95.91	4.92	113.47	100.00	8.46	23.08	272.98
56	63.71	96.16	5.61	113.75	100.00	10.39	25.91	249.34
57	11.51	85.96	1.03	97.30	100.00	2.98	6.10	204.80
58	13.20	86.15	1.10	92.48	100.00	3.52	6.20	175.83
59	24.69	82.17	2.33	90.32	100.00	7.06	11.05	156.48
60	27.75	84.43	2.60	90.37	100.00	8.55	12.63	147.72
61	33.68	83.87	3.39	92.07	100.00	9.85	17.84	181.07
62	34.30	83.50	3.45	94.55	100.00	10.11	18.59	183.88
63	15.42	90.95	1.16	98.27	100.00	3.48	5.46	156.63
64	14.09	90.04	1.08	98.48	100.00	3.38	5.29	156.58
65	NA	NA	NA	NA	NA	NA	NA	NA
66	42.65	104.46	2.71	89.51	100.00	9.25	15.23	164.66
67	45.99	93.52	3.24	88.70	100.00	10.15	16.94	166.90
68	45.76	88.26	3.42	85.10	100.00	11.48	16.93	147.43
69	34.49	104.15	2.42	89.98	100.00	4.95	11.56	233.69
70	34.66	97.20	2.74	94.13	100.00	9.34	13.80	147.78
71	33.44	87.06	2.59	85.01	100.00	14.00	13.40	95.74
72	26.84	65.98	2.43	73.91	100.00	18.65	12.55	67.29
73	23.00	52.27	2.42	66.51	100.00	22.90	12.58	54.91
74	30.58	89.44	2.24	82.76	100.00	5.34	11.28	211.18
75	32.59	93.33	2.45	86.96	100.00	8.97	13.09	145.85
76	34.19	95.70	2.21	74.80	100.00	13.57	12.65	93.19
77	33.57	84.01	2.17	63.03	100.00	19.38	13.18	68.00
78	NA	NA	NA	NA	NA	NA	NA	NA
79	15.19	91.09	1.37	106.52	100.00	3.71	6.85	184.75
80	23.25	91.48	2.08	104.89	100.00	5.85	10.43	178.25
81	27.72	92.23	2.51	108.67	100.00	6.39	12.32	192.74
82	40.02	92.74	3.69	107.70	100.00	9.83	19.15	194.87
83	39.94	85.81	3.93	101.03	100.00	10.65	20.15	189.22
84	51.46	95.15	5.03	117.44	100.00	11.75	25.69	218.63

	BF	BG	BH	BI	BJ
1	Air fuel	Air fuel	Specific	Turndown	Equivalent
2	ratio	ratio	gasification	ratio	ratio
3			rate		
4	(kg/kg)	(Nm3/kg)	(Nm3/m2h)	(%)	
5	2.73	2.11	626.37	20.22	0.51
6	2.32	1.80	1067.67	38.07	0.43
7	2.26	1.75	1795.50	62.25	0.42
8	1.95	1.51	2125.69	78.37	0.36
9	1.87	1.45	2279.72	83.98	0.35
10	1.86	1.44	2586.38	100.01	0.35
11	1.61	1.25	2560.79	113.18	0.30
12	1.08	0.84	2444.43	154.78	0.20
13	2.03	1.57	621.90	20.64	0.38
14	1.58	1.22	995.99	38.97	0.30
15	1.59	1.23	1427.80	54.21	0.30
16	1.47	1.14	1720.83	68.53	0.28
17	1.61	1.24	2087.85	78.69	0.30
18	1.62	1.25	2489.41	90.39	0.30
19	1.50	1.16	2607.13	100.00	0.28
20	1.33	1.03	2591.92	112.79	0.25
21	1.17	0.91	2722.53	131.60	0.22
22	1.55	1.20	507.85	19.00	0.29
23	1.63	1.26	1049.22	37.36	0.31
24	1.43	1.10	1326.80	51.53	0.27
25	1.32	1.02	1626.87	63.22	0.25
26	1.25	0.97	1948.73	76.41	0.23
27	1.26	0.97	2352.95	90.20	0.24
28	1.44	1.12	2942.32	100.00	0.27
29	1.30	1.00	3104.02	116.14	0.24
30	0.93	0.72	2579.32	135.60	0.17
31	1.33	1.03	635.07	30.88	0.25
32	1.48	1.15	1067.08	44.47	0.28
33	1.59	1.23	1268.96	48.06	0.30
34	1.45	1.12	1402.71	54.92	0.27
35	1.49	1.15	1879.18	67.85	0.28
36	1.47	1.14	2203.23	81.54	0.27
37	1.31	1.01	2415.32	100.00	0.24
38	1.06	0.82	2479.76	127.44	0.20
39	1.05	0.81	2584.77	136.69	0.20
40	1.49	1.15	839.74	40.67	0.28
41	1.58	1.22	1335.01	59.34	0.30
42	1.55	1.20	1731.59	72.04	0.29
43	1.45	1.12	2019.46	87.13	0.27
44	1.33	1.03	2134.81	100.00	0.25
45	1.05	0.81	2275.42	140.27	0.20

	BF	BG	BH	BI	BJ
46	1.03	0.80	2413.18	154.14	0.19
47	0.96	0.75	2547.61	170.97	0.18
48	NA	NA	NA	NA	NA
49	1.95	1.51	1274.17	46.05	0.37
50	1.76	1.37	1639.43	61.86	0.33
51	1.82	1.41	2057.68	72.57	0.34
52	1.92	1.49	2623.99	87.20	0.36
53	1.96	1.52	3111.59	100.01	0.37
54	1.94	1.50	3558.21	113.35	0.36
55	1.76	1.36	3575.40	129.64	0.33
56	1.72	1.33	3906.18	144.16	0.32
57	1.66	1.29	640.22	27.88	0.31
58	1.74	1.35	774.71	30.96	0.33
59	1.27	0.98	1423.67	69.24	0.24
60	1.24	0.96	1539.10	74.27	0.23
61	0.99	0.77	1691.43	99.99	0.19
62	1.13	0.87	1789.51	97.61	0.21
63	2.33	1.80	1080.77	28.76	0.44
64	2.33	1.81	975.13	26.20	0.44
65	NA	NA	NA	NA	NA
66	2.02	1.56	2533.05	72.80	0.38
67	1.92	1.48	2979.30	92.07	0.36
68	1.74	1.35	3023.54	99.99	0.33
69	1.32	1.02	1993.33	100.01	0.25
70	1.60	1.24	1989.44	87.60	0.30
71	2.27	1.76	2057.60	70.12	0.42
72	2.90	2.24	1859.52	56.69	0.54
73	3.29	2.54	1746.76	51.51	0.62
74	1.42	1.10	1890.78	100.01	0.27
75	1.65	1.28	1851.76	85.84	0.31
76	2.01	1.56	1799.39	68.57	0.38
77	2.36	1.82	1748.18	60.61	0.44
78	NA	NA	NA	NA	NA
79	1.75	1.35	919.12	29.53	0.33
80	1.74	1.34	1424.78	44.78	0.33
81	1.75	1.35	1736.77	53.85	0.33
82	1.63	1.26	2406.97	78.41	0.31
83	1.38	1.07	2390.56	90.90	0.26
84	1.61	1.25	3138.77	100.01	0.30

APPENDIX V

Energy balance data, gas heating value, cold gas efficiency data for runs 22-101

	A	B	C	D	E	F	G	H	I
1	Run	CO2	H2	CH4	CO	N2	Gas heat	Mass gas	Gas
2							value	flow rate	flowrate
3							dry	dry	dry
4		(%)	(%)	(%)	(%)	(%)	(MJ/Nm3)	(kg/h)	(Nm3/h)
5	R22	13.0	13.5	0.8	11.6	61.1	3.51	23.25	19.67
6	R23	12.8	14.5	0.8	14.6	57.3	4.01	39.19	33.52
7	R24	12.6	15.5	0.7	16.9	54.3	4.39	65.19	56.38
8	R25	12.3	18.4	0.6	18.9	49.8	4.97	74.83	66.75
9	R26	12.2	17.8	0.4	21.9	47.7	5.20	80.78	71.58
10	R27	11.9	15.9	0.5	21.9	49.8	4.99	93.21	81.21
11	R28	10.5	17.2	0.6	22.4	49.3	5.26	90.23	80.41
12	R29	9.9	18.5	0.5	23.5	47.6	5.53	84.69	76.76
13	R30	12.4	15.5	0.8	16.5	54.8	4.38	22.54	19.53
14	R31	11.2	16.5	0.7	21.3	50.3	5.07	35.49	31.27
15	R32	10.8	16.3	0.7	23.0	49.2	5.26	50.85	44.83
16	R33	9.8	17.7	0.8	24.1	47.6	5.62	59.99	54.03
17	R34	9.3	16.9	0.7	23.9	49.2	5.45	73.20	65.56
18	R35	9.1	17.9	0.7	24.5	47.8	5.66	86.26	78.17
19	R36	8.9	18.5	0.9	24.8	46.9	5.85	89.56	81.86
20	R37	8.8	17.8	1.2	25.2	47.0	5.93	89.51	81.39
21	R38	8.6	18.5	1.1	25.7	46.1	6.04	93.25	85.49
22	R39	11.4	16.2	0.8	18.7	52.9	4.75	18.16	15.95
23	R40	9.0	16.5	0.9	20.6	53.0	5.07	36.83	32.95
24	R41	8.6	15.5	0.9	24.5	50.5	5.43	46.94	41.66
25	R42	8.5	16.7	1.2	26.7	46.9	5.98	56.73	51.08
26	R43	8.5	17.3	0.9	28.5	44.8	6.17	67.62	61.19
27	R44	8.1	17.4	1.4	29.2	43.9	6.47	81.15	73.88
28	R45	8.2	16.9	1.3	28.9	44.7	6.32	102.13	92.39
29	R46	7.9	16.9	1.3	29.7	44.2	6.42	107.54	97.47
30	R47	7.8	16.5	1.5	29.5	44.7	6.43	89.59	80.99
31	R48	11.5	16.7	0.9	15.3	55.6	4.42	22.60	19.94
32	R49	10.5	17.1	0.8	18.5	53.1	4.84	37.60	33.51
33	R50	9.5	16.9	1.1	20.8	51.7	5.22	44.46	39.85
34	R51	8.3	16.3	0.9	25.6	48.9	5.67	49.12	44.05
35	R52	7.9	16.7	1.4	27.8	46.2	6.20	65.21	59.01
36	R53	8.3	16.9	1.5	26.6	46.7	6.11	76.45	69.18
37	R54	8.5	17.1	1.8	26.1	46.5	6.19	83.62	75.84
38	R55	8.9	16.8	1.7	25.8	46.8	6.08	86.39	77.86
39	R56	9.1	16.9	1.3	25.1	47.6	5.84	90.24	81.16
40	R57	8.1	16.4	0.9	15.3	59.3	4.38	29.34	26.37
41	R58	8.5	16.5	1.1	16.3	57.6	4.60	46.67	41.92
42	R59	9.8	16.9	1.6	18.6	53.1	5.14	60.64	54.37
43	R60	9.2	17.3	1.8	20.5	51.2	5.51	70.09	63.41
44	R61	9.8	17.8	1.7	19.7	51.0	5.44	74.02	67.03
45	R62	9.6	17.1	1.9	18.5	52.9	5.27	79.30	71.45

	A	B	C	D	E	F	G	H	I
46	R63	10.2	16.5	1.8	17.4	54.1	5.02	85.00	75.77
47	R64	11.3	16.4	2.1	17.1	53.1	5.09	90.32	79.99
48	R65	NA	NA	NA	NA	NA	NA	NA	NA
49	R66	9.8	15.2	1.4	13.0	60.6	4.14	45.45	40.01
50	R67	11.5	15.6	1.8	13.9	57.2	4.46	58.76	51.48
51	R68	12.6	15.1	2.1	15.1	55.1	4.67	74.53	64.61
52	R69	13.2	15.1	2.1	14.8	54.8	4.63	95.39	82.39
53	R70	14.5	14.9	2.3	14.2	54.1	4.61	114.15	97.70
54	R71	15.9	14.8	2.5	13.7	53.1	4.61	131.66	111.73
55	R72	16.3	14.5	2.4	11.9	54.9	4.31	133.07	112.27
56	R73	16.8	14.6	2.6	11.6	54.4	4.36	145.54	122.65
57	R74	11.6	9.0	0.8	17.1	61.5	3.63	24.61	20.10
58	R75	12.7	10.4	0.7	17.1	59.1	3.77	29.59	24.33
59	R76	12.8	15.6	0.8	18.5	52.3	4.65	51.68	44.70
60	R77	13.2	16.3	0.7	19.1	50.7	4.77	55.64	48.33
61	R78	11.9	17.3	0.6	20.5	49.7	5.04	60.07	53.11
62	R79	10.2	15.6	0.6	21.3	52.3	4.92	63.98	56.19
63	R80	12.8	13.5	0.8	17.3	55.6	4.23	40.06	33.94
64	R81	11.9	12.6	0.9	18.3	56.3	4.28	36.25	30.62
65	R82	NA	NA	NA	NA	NA	NA	NA	NA
66	R83	15.2	11.4	0.7	20.5	52.2	4.32	97.24	79.54
67	R84	12.5	12.8	0.7	20.8	53.2	4.54	111.04	93.55
68	R85	11.8	14.5	0.8	21.2	51.7	4.85	110.29	94.94
69	R86	15.5	14.8	1.1	22.4	46.2	5.16	74.05	62.59
70	R87	15.4	15.5	1.2	18.5	49.4	4.79	73.32	62.47
71	R88	14.5	13.6	1.0	16.8	54.1	4.26	76.91	64.61
72	R89	12.1	12.5	1.3	12.3	61.8	3.67	69.16	58.39
73	R90	11.0	13.0	1.3	6.9	67.8	3.05	64.21	54.85
74	R91	13.5	12.7	1.0	20.5	52.3	4.61	70.87	59.37
75	R92	16.3	12.9	0.9	16.8	53.1	4.13	70.47	58.15
76	R93	20.7	10.6	0.9	14.6	53.2	3.55	71.76	56.50
77	R94	22.4	9.5	1.1	10.3	56.7	2.95	71.02	54.89
78	R95	NA	NA	NA	NA	NA	NA	NA	NA
79	R96	14.0	15.2	1.3	14.7	54.8	4.31	33.67	28.86
80	R97	13.5	16.5	1.1	15.7	53.2	4.53	51.41	44.74
81	R98	13.0	17.3	0.9	16.0	52.8	4.59	62.02	54.53
82	R99	12.5	17.8	1.0	16.8	51.9	4.79	85.20	75.58
83	R100	10.8	18.7	1.0	18.4	51.1	5.11	82.93	75.06
84	R101	9.9	18.9	1.1	20.0	50.1	5.38	107.97	98.56

	J	K	L	M	N	O	P
1	Wood	Mass	Energy	Latent	Total	Energy	Sensible
2	input	water in	wood	heat	energy	in gas	in gas
3	(daf)	air		water in air	in		
4	(kg/h)	(kg/h)	(MJ/h)	(MJ/h)	(MJ/h)	(MJ/h)	(MJ/h)
5	7.64	0.56	140.85	1.38	142.23	68.97	5.85
6	14.38	0.90	265.12	2.21	267.33	134.51	10.07
7	23.51	1.43	433.44	3.52	436.96	247.57	17.02
8	29.60	1.55	545.72	3.81	549.53	332.03	20.15
9	31.72	1.59	584.81	3.91	588.72	372.00	24.13
10	37.77	1.89	696.35	4.65	701.00	405.57	29.01
11	42.75	1.85	788.16	4.55	792.71	423.20	28.37
12	58.46	1.71	1077.80	4.21	1082.01	424.34	27.57
13	9.15	0.50	168.69	1.23	169.92	85.55	4.82
14	17.27	0.73	318.40	1.80	320.19	158.68	8.32
15	24.03	1.03	443.03	2.53	445.56	235.97	12.70
16	30.38	1.20	560.10	2.95	563.05	303.70	18.62
17	34.88	1.51	643.07	3.72	646.78	357.56	23.58
18	40.07	1.74	738.75	4.28	743.03	442.23	27.87
19	44.33	1.79	817.29	4.41	821.70	478.99	29.15
20	50.00	1.79	921.83	4.41	926.23	482.79	29.88
21	58.34	1.84	1075.59	4.53	1080.11	516.74	32.32
22	9.45	0.39	174.22	0.96	175.18	75.72	4.16
23	18.57	0.82	342.37	2.02	344.38	166.91	9.29
24	25.62	0.98	472.34	2.41	474.75	226.23	13.01
25	31.43	1.12	579.46	2.76	582.22	305.50	17.40
26	37.99	1.28	700.40	3.15	703.55	377.26	21.62
27	44.85	1.51	826.88	3.72	830.59	477.66	27.30
28	49.72	1.93	916.66	4.75	921.41	584.26	36.37
29	57.74	2.00	1064.52	4.92	1069.45	626.24	39.98
30	67.42	1.69	1242.99	4.16	1247.15	520.61	34.91
31	14.47	0.52	266.78	1.28	268.06	88.17	5.86
32	20.84	0.83	384.22	2.04	386.26	162.10	10.14
33	22.52	0.96	415.19	2.36	417.55	208.08	13.09
34	25.73	1.01	474.37	2.49	476.86	249.83	15.36
35	31.79	1.27	586.10	3.13	589.22	365.81	21.45
36	38.20	1.51	704.27	3.72	707.99	422.89	25.66
37	46.85	1.65	863.75	4.06	867.81	469.80	30.10
38	59.70	1.70	1100.66	4.18	1104.84	473.29	32.52
39	64.04	1.80	1180.67	4.43	1185.10	474.30	35.31
40	18.21	0.73	335.73	1.80	337.53	115.59	8.29
41	26.56	1.13	489.67	2.78	492.45	192.92	15.21
42	32.25	1.35	594.58	3.32	597.90	279.59	20.16
43	39.00	1.52	719.02	3.74	722.76	349.58	24.11
44	44.76	1.60	825.22	3.94	829.16	364.38	26.37
45	62.79	1.77	1157.63	4.36	1161.98	376.87	30.42

	J	K	L	M	N	O	P
46	68.99	1.91	1271.93	4.70	1276.63	380.32	33.63
47	76.52	1.98	1410.76	4.87	1415.63	406.99	36.30
48	NA	NA	NA	NA	NA	NA	NA
49	21.56	1.13	397.49	2.78	400.27	165.59	14.24
50	28.96	1.38	533.92	3.40	537.32	229.73	19.41
51	33.98	1.66	626.47	4.09	630.56	301.70	25.21
52	40.83	2.11	752.76	5.19	757.96	381.60	33.32
53	46.82	2.47	863.20	6.08	869.28	450.38	41.69
54	53.07	2.77	978.43	6.82	985.24	515.46	50.39
55	60.70	2.88	1119.10	7.09	1126.18	483.67	51.68
56	67.50	3.12	1244.46	7.68	1252.14	535.06	58.39
57	12.90	0.58	237.83	1.43	239.26	72.89	7.68
58	14.33	0.67	264.20	1.65	265.84	91.61	8.42
59	32.04	1.09	590.71	2.68	593.39	207.67	17.58
60	34.37	1.14	633.66	2.81	636.47	230.59	19.89
61	46.28	1.23	853.24	3.03	856.27	267.45	21.85
62	45.18	1.37	832.96	3.37	836.33	276.45	23.72
63	14.08	0.88	259.59	2.17	261.75	143.44	10.12
64	12.83	0.81	236.54	1.99	238.53	130.97	9.56
65	NA	NA	NA	NA	NA	NA	NA
66	35.65	1.94	657.26	4.77	662.04	343.81	34.94
67	45.09	2.32	831.30	5.71	837.01	424.63	39.59
68	48.97	2.29	902.84	5.64	908.47	460.11	40.04
69	38.12	1.35	702.80	3.32	706.12	322.68	18.31
70	33.39	1.44	615.59	3.54	619.14	299.36	16.64
71	26.73	1.63	492.81	4.01	496.82	274.93	18.02
72	21.61	1.69	398.41	4.16	402.57	214.05	15.01
73	19.63	1.74	361.91	4.28	366.19	167.17	13.79
74	37.83	1.45	697.45	3.57	701.02	273.56	17.37
75	32.47	1.44	598.63	3.54	602.18	239.94	16.57
76	25.94	1.40	478.24	3.45	481.69	200.84	16.07
77	22.93	1.45	422.75	3.57	426.32	161.97	15.51
78	NA	NA	NA	NA	NA	NA	NA
79	15.69	0.74	289.27	1.82	291.09	124.49	9.55
80	23.80	1.11	438.79	2.73	441.52	202.51	15.44
81	28.62	1.34	527.65	3.30	530.95	250.12	20.93
82	41.67	1.83	768.25	4.50	772.75	362.14	29.87
83	48.31	1.79	890.67	4.41	895.07	383.44	29.92
84	53.14	2.31	979.72	5.68	985.40	529.83	41.24

	Q	R	S	T	U	V	W
1	Total	Total	Total	Sensible	Total	Tar	Heat
2	energy	water	energy	heat	energy	output	combust
3	gas	output	in water	in water	in water		tar
4	(MJ/h)	(kg/h)	(MJ/h)	(MJ/h)	(MJ/h)	(kg/h)	(MJ/h)
5	74.82	2.79	7.44	1.08	8.52	0.35	12.30
6	144.59	5.26	14.04	2.08	16.11	0.97	34.09
7	264.60	7.54	20.12	3.02	23.14	0.99	34.79
8	352.18	10.08	26.90	4.17	31.07	0.98	34.44
9	396.12	11.29	30.13	5.18	35.31	1.20	42.17
10	434.59	14.67	39.14	7.01	46.16	1.33	46.74
11	451.57	17.45	46.56	8.43	54.99	2.68	94.18
12	451.90	20.88	55.71	10.44	66.15	3.46	121.58
13	90.37	3.75	10.01	1.23	11.24	0.95	33.38
14	167.00	5.23	13.96	1.88	15.84	1.33	46.74
15	248.67	7.85	20.95	3.01	23.96	1.89	66.41
16	322.32	10.68	28.50	5.09	33.59	1.98	69.58
17	381.13	13.00	34.69	6.43	41.12	2.16	75.90
18	470.10	14.86	39.65	7.38	47.03	1.43	50.25
19	508.14	15.89	42.40	7.95	50.34	2.74	96.28
20	512.66	17.05	45.49	8.74	54.24	3.56	125.10
21	549.07	19.54	52.14	10.40	62.54	3.89	136.69
22	79.88	3.50	9.34	1.23	10.57	0.97	34.09
23	176.20	6.24	16.65	2.42	19.07	1.79	62.90
24	239.24	8.28	22.09	3.53	25.62	1.96	68.87
25	322.90	10.58	28.23	4.98	33.22	2.15	75.55
26	398.88	13.19	35.20	6.48	41.67	2.46	86.44
27	504.96	17.15	45.76	8.86	54.63	3.22	113.15
28	620.64	20.69	55.21	11.32	66.53	3.21	112.80
29	666.22	23.22	61.96	13.26	75.22	3.64	127.91
30	555.52	23.51	62.73	14.07	76.80	3.73	131.07
31	94.04	4.44	11.85	1.77	13.62	1.95	68.52
32	172.24	5.92	15.80	2.45	18.25	2.03	71.33
33	221.17	7.30	19.48	3.30	22.78	1.86	65.36
34	265.19	8.60	22.95	4.13	27.08	2.04	71.69
35	387.26	11.26	30.05	5.69	35.73	2.33	81.88
36	448.56	14.41	38.45	7.43	45.88	2.74	96.28
37	499.90	17.02	45.41	9.41	54.83	2.89	101.55
38	505.80	19.97	53.29	11.55	64.83	3.87	135.99
39	509.61	20.11	53.66	12.09	65.75	4.31	151.45
40	123.88	6.00	16.01	2.60	18.61	2.84	99.80
41	208.13	8.53	22.76	4.27	27.03	3.31	116.31
42	299.75	11.54	30.79	5.89	36.68	3.70	130.02
43	373.69	14.91	39.78	7.88	47.66	4.52	158.83
44	390.75	16.05	42.83	8.78	51.61	4.89	171.83
45	407.30	18.45	49.23	10.87	60.10	5.56	195.38

	Q	R	S	T	U	V	W
46	413.94	20.26	54.06	12.31	66.37	5.88	206.62
47	443.29	23.46	62.60	14.49	77.08	5.97	209.79
48	NA	NA	NA	NA	NA	NA	NA
49	179.83	6.82	18.20	3.28	21.48	1.78	62.55
50	249.14	9.30	24.82	4.72	29.53	2.02	70.98
51	326.90	11.19	29.86	5.81	35.67	2.67	93.82
52	414.92	13.82	36.88	7.42	44.29	3.05	107.18
53	492.07	17.29	46.14	9.70	55.83	3.44	120.88
54	565.85	20.26	54.06	11.91	65.97	3.78	132.83
55	535.34	23.08	61.58	13.77	75.35	4.06	142.67
56	593.45	25.91	69.14	15.97	85.10	5.61	197.14
57	80.57	6.10	16.28	2.93	19.20	1.46	51.30
58	100.04	6.20	16.54	2.71	19.25	1.48	52.01
59	225.24	11.05	29.48	5.77	35.26	4.20	147.59
60	250.48	12.63	33.70	6.93	40.64	4.32	151.80
61	289.31	17.84	47.60	9.97	57.57	5.19	182.38
62	300.17	18.59	49.60	10.59	60.19	5.26	184.84
63	153.56	5.46	14.57	2.12	16.69	0.88	30.92
64	140.53	5.29	14.12	2.14	16.26	0.93	32.68
65	NA	NA	NA	NA	NA	NA	NA
66	378.75	15.23	40.64	8.41	49.05	1.04	36.55
67	464.22	16.94	45.20	9.28	54.48	1.66	58.33
68	500.15	16.93	45.17	9.44	54.62	1.67	58.68
69	340.99	11.56	30.85	4.39	35.24	1.76	61.85
70	316.00	13.80	36.82	4.81	41.63	2.02	70.98
71	292.96	13.40	35.76	4.82	40.58	2.03	71.33
72	229.06	12.55	33.49	4.18	37.67	2.44	85.74
73	180.97	12.58	33.57	4.15	37.72	2.62	92.07
74	290.93	11.28	30.10	4.25	34.35	2.06	72.39
75	256.51	13.09	34.93	4.73	39.66	2.24	78.71
76	216.91	12.65	33.75	4.35	38.10	1.74	61.14
77	177.48	13.18	35.17	4.42	39.59	1.11	39.01
78	NA	NA	NA	NA	NA	NA	NA
79	134.05	6.85	18.28	2.99	21.26	1.46	51.30
80	217.95	10.43	27.83	4.81	32.64	1.64	57.63
81	271.05	12.32	32.87	6.39	39.26	2.02	70.98
82	392.01	19.15	51.10	10.31	61.41	2.11	74.15
83	413.35	20.15	53.77	11.17	64.93	2.94	103.31
84	571.08	25.69	68.55	15.07	83.62	3.10	108.93

	X	Y	Z	AA	AB	AC	AD
1	Sensible	Total energy	Char	Heat	Sensible	Total	Total
2	heat of	from tar	output	combust	heat	energy	heat
3	tar			char	char	in char	losses
4	(MJ/h)	(MJ/h)	(kg/h)	(MJ/h)	(MJ/h)	(MJ/h)	(MJ/h)
5	0.53	12.83	0.84	21.22	0.14	21.36	20.12
6	0.54	34.63	1.09	27.53	0.14	27.67	44.10
7	0.55	35.34	1.34	33.85	0.14	33.99	65.72
8	0.57	35.00	1.07	27.03	0.15	27.18	85.47
9	0.63	42.80	1.16	29.30	0.16	29.47	97.56
10	0.65	47.39	1.13	28.54	0.17	28.71	110.79
11	0.66	94.84	2.03	51.28	0.17	51.45	123.50
12	0.68	122.27	3.49	88.16	0.18	88.34	140.12
13	0.45	33.83	0.89	22.48	0.12	22.60	27.91
14	0.49	47.23	1.46	36.88	0.13	37.01	44.38
15	0.53	66.94	1.68	42.44	0.14	42.57	65.92
16	0.65	70.23	1.94	49.00	0.17	49.17	85.13
17	0.68	76.58	2.02	51.03	0.18	51.20	97.62
18	0.68	50.93	2.47	62.39	0.18	62.57	110.60
19	0.68	96.97	2.57	64.92	0.18	65.10	121.19
20	0.70	125.80	3.56	89.93	0.18	90.11	137.42
21	0.73	137.42	4.76	120.24	0.19	120.43	154.16
22	0.48	34.57	1.12	28.29	0.13	28.42	29.00
23	0.53	63.43	1.78	44.96	0.14	45.10	45.77
24	0.58	69.46	2.26	57.09	0.15	57.24	67.82
25	0.65	76.20	2.20	55.57	0.17	55.74	86.94
26	0.67	87.12	2.94	74.26	0.18	74.44	99.79
27	0.71	113.86	3.13	79.06	0.18	79.25	112.66
28	0.75	113.55	2.95	74.52	0.20	74.71	125.28
29	0.78	128.69	3.61	91.19	0.20	91.39	142.48
30	0.82	131.89	4.73	119.48	0.21	119.69	164.11
31	0.55	69.07	2.01	50.77	0.14	50.91	32.36
32	0.57	71.90	2.35	59.36	0.15	59.51	49.80
33	0.62	65.98	2.95	74.52	0.16	74.68	72.67
34	0.66	72.34	3.34	84.37	0.17	84.54	92.79
35	0.69	82.57	3.74	94.47	0.18	94.65	105.78
36	0.71	96.99	3.84	97.00	0.18	97.18	119.45
37	0.76	102.31	4.06	102.56	0.20	102.75	135.74
38	0.79	136.78	4.88	123.27	0.21	123.48	156.97
39	0.82	152.28	4.92	124.28	0.21	124.49	179.23
40	0.59	100.39	3.15	79.57	0.15	79.72	31.94
41	0.69	117.00	3.20	80.83	0.18	81.01	49.90
42	0.70	130.72	3.53	89.17	0.18	89.35	72.63
43	0.72	159.56	4.28	108.11	0.19	108.30	92.77
44	0.75	172.58	4.56	115.19	0.20	115.38	105.38
45	0.81	196.19	4.83	122.01	0.21	122.22	131.84

	X	Y	Z	AA	AB	AC	AD
46	0.83	207.46	4.94	124.78	0.22	125.00	169.54
47	0.85	210.63	5.01	126.55	0.22	126.77	193.46
48	NA	NA	NA	NA	NA	NA	NA
49	0.66	63.21	2.21	55.82	0.17	56.00	31.89
50	0.69	71.68	2.68	67.70	0.18	67.88	49.31
51	0.71	94.54	2.76	69.72	0.19	69.90	72.48
52	0.73	107.91	3.01	76.03	0.19	76.22	92.53
53	0.77	121.65	3.31	83.61	0.20	83.81	105.85
54	0.81	133.63	4.03	101.80	0.21	102.01	131.59
55	0.82	143.49	4.85	122.51	0.21	122.72	169.31
56	0.84	197.98	5.02	126.81	0.22	127.03	193.72
57	0.66	51.96	2.13	53.80	0.17	53.98	39.69
58	0.60	52.61	2.21	55.82	0.16	55.98	59.29
59	0.72	148.30	3.12	78.81	0.19	79.00	85.57
60	0.75	152.56	3.53	89.17	0.20	89.36	111.10
61	0.77	183.14	5.67	143.22	0.20	143.42	140.44
62	0.78	185.62	6.02	152.07	0.20	152.27	175.52
63	0.53	31.45	1.04	26.27	0.14	26.41	31.94
64	0.55	33.24	1.04	26.27	0.14	26.42	31.89
65	NA	NA	NA	NA	NA	NA	NA
66	0.76	37.30	1.03	26.02	0.20	26.21	111.14
67	0.75	59.08	1.84	46.48	0.20	46.67	153.16
68	0.76	59.45	1.92	48.50	0.20	48.70	175.20
69	0.52	62.37	1.89	47.74	0.14	47.88	175.60
70	0.48	71.46	1.95	49.26	0.12	49.38	133.33
71	0.49	71.83	1.93	48.75	0.13	48.88	98.64
72	0.46	86.20	2.05	51.78	0.12	51.90	70.04
73	0.45	92.52	2.19	55.32	0.12	55.44	47.97
74	0.52	72.90	2.21	55.82	0.13	55.96	175.79
75	0.49	79.21	2.45	61.89	0.13	62.02	133.44
76	0.47	61.61	2.25	56.84	0.12	56.96	98.74
77	0.46	39.46	2.40	60.62	0.12	60.74	70.68
78	NA	NA	NA	NA	NA	NA	NA
79	0.60	51.90	1.98	50.01	0.16	50.17	46.62
80	0.63	58.26	2.23	56.33	0.16	56.49	68.54
81	0.71	71.69	2.69	67.95	0.19	68.13	95.90
82	0.74	74.88	2.90	73.25	0.19	73.45	126.73
83	0.76	104.07	3.12	78.81	0.20	79.01	164.51
84	0.80	109.74	3.14	79.32	0.21	79.53	193.05

	AE	AF	AG	AH	AI	AJ
1	% Heat loss	Total	Energy	Cold gas	Hot gas	Raw gas
2	to chemical	energy	balance	efficiency	efficiency	efficiency
3	energy wood	output	closure			gas
4	(%)	(MJ/h)	(%)	(%)	(%)	(%)
5	14.28	137.64	96.77	48.97	53.12	62.22
6	16.63	267.10	99.91	50.74	54.54	67.60
7	15.16	422.79	96.76	57.12	61.05	69.20
8	15.66	530.89	96.61	60.84	64.53	70.95
9	16.68	601.25	102.13	63.61	67.74	75.05
10	15.91	667.64	95.24	58.24	62.41	69.22
11	15.67	776.35	97.94	53.69	57.29	69.33
12	13.00	868.78	80.29	39.37	41.93	53.27
13	16.54	185.95	109.43	50.71	53.57	73.63
14	13.94	311.46	97.27	49.84	52.45	67.28
15	14.88	448.06	100.56	53.26	56.13	71.24
16	15.20	560.45	99.54	54.22	57.55	70.09
17	15.18	647.65	100.13	55.60	59.27	71.18
18	14.97	741.23	99.76	59.86	63.63	70.53
19	14.83	841.74	102.44	58.61	62.17	74.04
20	14.91	920.23	99.35	52.37	55.61	69.26
21	14.33	1023.62	94.77	48.04	51.05	63.82
22	16.65	182.44	104.14	43.46	45.85	65.69
23	13.37	349.57	101.50	48.75	51.46	69.99
24	14.36	459.38	96.76	47.90	50.65	65.36
25	15.00	574.99	98.76	52.72	55.72	68.87
26	14.25	701.90	99.77	53.86	56.95	69.39
27	13.62	865.35	104.19	57.77	61.07	74.84
28	13.67	1000.71	108.61	63.74	67.71	80.09
29	13.38	1104.00	103.23	58.83	62.58	74.67
30	13.20	1048.02	84.03	41.88	44.69	55.30
31	12.13	260.00	96.99	33.05	35.25	61.14
32	12.96	371.69	96.23	42.19	44.83	63.54
33	17.50	457.28	109.51	50.12	53.27	69.16
34	19.56	541.95	113.65	52.67	55.90	71.15
35	18.05	706.00	119.82	62.42	66.08	80.16
36	16.96	808.06	114.13	60.05	63.69	77.46
37	15.72	895.53	103.19	54.39	57.88	69.72
38	14.26	987.86	89.41	43.00	45.95	58.38
39	15.18	1031.35	87.03	40.17	43.16	56.06
40	9.51	354.55	105.04	34.43	36.90	66.80
41	10.19	483.07	98.09	39.40	42.50	66.40
42	12.22	629.13	105.22	47.02	50.41	72.40
43	12.90	781.98	108.19	48.62	51.97	74.16
44	12.77	835.70	100.79	44.16	47.35	68.26
45	11.39	917.64	78.97	32.56	35.18	52.13

	AE	AF	AG	AH	AI	AJ
46	13.33	982.31	76.95	29.90	32.54	48.85
47	13.71	1051.24	74.26	28.85	31.42	46.35
48	NA	NA	NA	NA	NA	NA
49	8.02	352.40	88.04	41.66	45.24	61.14
50	9.24	467.54	87.01	43.03	46.66	60.09
51	11.57	599.49	95.07	48.16	52.18	67.27
52	12.29	735.87	97.09	50.69	55.12	69.45
53	12.26	859.21	98.84	52.18	57.01	71.10
54	13.45	999.06	101.40	52.68	57.83	71.49
55	15.13	1046.22	92.90	43.22	47.84	60.66
56	15.57	1197.28	95.62	43.00	47.69	63.60
57	16.69	245.40	102.57	30.65	33.88	55.73
58	22.44	287.17	108.02	34.68	37.86	57.78
59	14.49	573.37	96.63	35.16	38.13	63.24
60	17.53	644.13	101.20	36.39	39.53	63.60
61	16.46	813.88	95.05	31.35	33.91	55.37
62	21.07	873.77	104.48	33.19	36.04	58.32
63	12.30	260.05	99.35	55.26	59.15	71.27
64	13.48	248.33	104.11	55.37	59.41	73.46
65	NA	NA	NA	NA	NA	NA
66	16.91	602.45	91.00	52.31	57.63	63.30
67	18.42	777.61	92.90	51.08	55.84	62.95
68	19.41	838.11	92.25	50.96	55.40	61.98
69	24.99	662.07	93.76	45.91	48.52	57.39
70	21.66	611.80	98.82	48.63	51.33	62.94
71	20.02	552.88	111.28	55.79	59.45	74.02
72	17.58	474.87	117.96	53.73	57.49	79.13
73	13.25	414.61	113.22	46.19	50.00	75.57
74	25.20	629.93	89.86	39.22	41.71	52.17
75	22.29	570.83	94.79	40.08	42.85	56.08
76	20.65	472.33	98.06	42.00	45.36	58.24
77	16.72	387.96	91.00	38.31	41.98	51.32
78	NA	NA	NA	NA	NA	NA
79	16.12	304.00	104.44	43.04	46.34	64.28
80	15.62	433.89	98.27	46.15	49.67	62.95
81	18.17	546.04	102.84	47.40	51.37	64.96
82	16.50	728.48	94.27	47.14	51.03	60.77
83	18.47	825.87	92.27	43.05	46.41	58.09
84	19.70	1037.01	105.24	54.08	58.29	69.49

	AK	AL	AM	AN	AO	AP
1	Sensible	Mass flow	Latent	Sensible	Total	Sensible
2	energy	water in	water	water	energy in	tar
3	gas	gas	gas	in gas	product gas	
4	(MJ/h)	(kg/h)	(MJ/h)	(MJ/h)	(MJ/h)	(MJ/h)
5	0.11	1.88	4.63	0.01	73.72	0.00
6	0.28	3.48	8.56	0.04	143.40	0.02
7	0.51	5.95	14.64	0.07	262.80	0.02
8	1.10	8.40	20.67	0.19	353.99	0.03
9	1.33	9.98	24.56	0.25	398.13	0.04
10	1.71	13.09	32.21	0.37	439.86	0.05
11	1.80	14.36	35.34	0.44	460.78	0.11
12	1.83	14.68	36.13	0.49	462.78	0.16
13	0.17	1.78	4.38	0.02	90.12	0.02
14	0.30	3.04	7.48	0.04	166.50	0.02
15	0.65	5.53	13.61	0.11	250.33	0.05
16	0.82	7.09	17.45	0.15	322.12	0.06
17	1.20	8.87	21.83	0.22	380.81	0.08
18	1.27	10.72	26.38	0.24	470.13	0.05
19	1.47	11.51	28.33	0.29	509.07	0.10
20	1.47	12.27	30.20	0.31	514.76	0.13
21	1.76	13.55	33.35	0.39	552.24	0.16
22	0.17	1.55	3.81	0.02	79.73	0.02
23	0.44	3.71	9.13	0.07	176.55	0.05
24	0.69	5.33	13.12	0.12	240.16	0.06
25	0.86	7.22	17.77	0.17	324.29	0.07
26	1.36	9.00	22.15	0.28	401.04	0.11
27	1.56	12.32	30.32	0.36	509.90	0.13
28	1.83	16.01	39.40	0.44	625.94	0.12
29	2.31	17.42	42.87	0.57	671.99	0.17
30	1.99	16.60	40.85	0.57	564.03	0.18
31	0.27	2.03	5.00	0.04	93.47	0.05
32	0.41	3.56	8.76	0.06	171.32	0.05
33	0.55	4.77	11.74	0.09	220.46	0.05
34	0.69	5.98	14.72	0.13	265.36	0.06
35	1.05	8.14	20.03	0.20	387.10	0.08
36	1.21	10.33	25.42	0.25	449.77	0.09
37	1.67	12.13	29.85	0.37	501.69	0.12
38	1.67	13.20	32.49	0.39	507.83	0.16
39	1.74	12.83	31.57	0.38	508.00	0.18
40	0.34	2.97	7.31	0.05	123.29	0.07
41	0.66	5.04	12.40	0.11	206.09	0.10
42	0.84	7.06	17.37	0.15	297.96	0.11
43	1.02	8.81	21.68	0.20	372.47	0.14
44	1.07	9.67	23.80	0.21	389.46	0.15
45	1.49	11.50	28.30	0.33	407.00	0.22

	AK	AL	AM	AN	AO	AP
46	1.63	13.07	32.17	0.38	414.50	0.24
47	1.82	14.63	36.00	0.45	445.26	0.26
48	NA	NA	NA	NA	NA	NA
49	0.47	4.46	10.98	0.07	177.11	0.04
50	0.60	6.34	15.60	0.10	246.03	0.04
51	0.87	8.20	20.18	0.15	322.90	0.07
52	1.01	10.63	26.16	0.17	408.94	0.07
53	1.87	14.17	34.87	0.36	487.48	0.12
54	1.96	16.87	41.52	0.38	559.32	0.12
55	2.25	19.55	48.11	0.51	534.54	0.15
56	2.89	21.95	54.02	0.67	592.63	0.24
57	0.34	2.69	6.62	0.06	79.91	0.04
58	0.29	3.38	8.32	0.05	100.27	0.03
59	0.77	6.11	15.04	0.14	223.61	0.13
60	1.01	7.91	19.47	0.22	251.29	0.17
61	1.11	9.00	22.15	0.25	290.96	0.21
62	1.25	9.92	24.41	0.30	302.41	0.22
63	0.53	4.43	10.90	0.09	154.96	0.02
64	0.51	4.25	10.46	0.09	142.03	0.03
65	NA	NA	NA	NA	NA	NA
66	1.84	14.19	34.92	0.41	380.98	0.04
67	1.78	15.39	37.87	0.38	464.66	0.06
68	1.77	15.69	38.61	0.39	500.88	0.06
69	0.96	8.01	19.71	0.16	343.51	0.05
70	0.84	7.40	18.21	0.13	318.54	0.05
71	0.77	7.44	18.31	0.11	294.13	0.04
72	0.57	6.05	14.89	0.08	229.59	0.04
73	0.46	5.73	14.10	0.06	181.79	0.04
74	0.96	7.47	18.38	0.16	293.06	0.06
75	0.74	6.59	16.22	0.11	257.01	0.05
76	0.67	6.47	15.92	0.09	217.52	0.03
77	0.61	6.25	15.38	0.08	178.05	0.02
78	NA	NA	NA	NA	NA	NA
79	0.55	4.18	10.29	0.11	135.44	0.05
80	0.71	5.85	14.40	0.12	217.74	0.05
81	0.89	7.33	18.04	0.16	269.21	0.06
82	1.22	11.44	28.15	0.25	391.77	0.07
83	1.22	11.42	28.10	0.26	413.02	0.09
84	1.83	16.74	41.20	0.43	573.29	0.11

	AQ	AR	AS	AT	AU	AV
1	Total	Sensible	Total	Condensate	Water in	Latent
2	energy	char	energy	output	condensate	water in
3	tar		in char			condensate
4	(MJ/h)	(MJ/h)	(MJ/h)	(kg/h)	(kg/h)	(MJ/h)
5	12.30	0.00	21.22	0.92	0.91	2.25
6	34.10	0.00	27.54	1.79	1.78	4.37
7	34.81	0.01	33.85	1.60	1.59	3.91
8	34.47	0.01	27.04	1.69	1.68	4.13
9	42.21	0.01	29.31	1.32	1.31	3.22
10	46.79	0.01	28.55	1.60	1.59	3.91
11	94.29	0.02	51.30	3.12	3.10	7.62
12	121.74	0.04	88.20	6.25	6.20	15.26
13	33.40	0.00	22.48	1.99	1.97	4.86
14	46.76	0.01	36.89	2.21	2.19	5.40
15	66.47	0.01	42.45	2.34	2.32	5.71
16	69.64	0.01	49.02	3.62	3.59	8.84
17	75.98	0.02	51.04	4.16	4.13	10.16
18	50.30	0.02	62.41	4.17	4.14	10.18
19	96.38	0.02	64.94	4.41	4.37	10.77
20	125.22	0.03	89.96	4.82	4.78	11.77
21	136.85	0.05	120.28	6.04	5.99	14.75
22	34.11	0.01	28.30	1.96	1.94	4.78
23	62.95	0.01	44.97	2.55	2.53	6.23
24	68.94	0.02	57.10	2.97	2.95	7.25
25	75.62	0.02	55.59	3.38	3.35	8.25
26	86.55	0.03	74.29	4.22	4.19	10.30
27	113.28	0.03	79.09	4.87	4.83	11.89
28	112.92	0.03	74.54	4.71	4.67	11.50
29	128.08	0.04	91.23	5.84	5.79	14.26
30	131.25	0.05	119.53	6.96	6.90	16.99
31	68.57	0.01	50.78	2.43	2.41	5.93
32	71.38	0.01	59.37	2.38	2.36	5.81
33	65.41	0.02	74.54	2.55	2.53	6.23
34	71.75	0.02	84.39	2.64	2.62	6.45
35	81.96	0.03	94.50	3.14	3.11	7.67
36	96.38	0.03	97.03	4.11	4.08	10.03
37	101.68	0.04	102.60	4.93	4.89	12.04
38	136.15	0.05	123.32	6.83	6.78	16.67
39	151.63	0.05	124.33	7.33	7.27	17.89
40	99.87	0.02	79.59	3.05	3.03	7.45
41	116.41	0.02	80.86	3.52	3.49	8.59
42	130.13	0.03	89.19	4.51	4.47	11.01
43	158.97	0.03	108.14	6.15	6.10	15.01
44	171.99	0.03	115.22	6.43	6.38	15.70
45	195.60	0.05	122.05	7.00	6.94	17.09

	AQ	AR	AS	AT	AU	AV
46	206.87	0.05	124.83	7.25	7.19	17.70
47	210.04	0.05	126.60	8.90	8.83	21.73
48	NA	NA	NA	NA	NA	NA
49	62.59	0.01	55.84	2.37	2.35	5.79
50	71.03	0.01	67.71	2.98	2.96	7.28
51	93.89	0.02	69.73	3.02	3.00	7.37
52	107.25	0.02	76.05	3.22	3.19	7.86
53	121.00	0.03	83.64	3.15	3.12	7.69
54	132.95	0.03	101.83	3.42	3.39	8.35
55	142.82	0.04	122.55	3.56	3.53	8.69
56	197.37	0.05	126.86	4.00	3.97	9.77
57	51.35	0.02	53.82	3.44	3.41	8.40
58	52.04	0.01	55.84	2.84	2.82	6.93
59	147.72	0.02	78.84	4.98	4.94	12.16
60	151.97	0.03	89.20	4.75	4.71	11.60
61	182.58	0.05	143.28	8.91	8.84	21.75
62	185.06	0.06	152.13	8.74	8.67	21.34
63	30.95	0.01	26.28	1.03	1.02	2.51
64	32.71	0.01	26.28	1.05	1.04	2.56
65	NA	NA	NA	NA	NA	NA
66	36.59	0.01	26.03	1.04	1.03	2.54
67	58.39	0.02	46.49	1.56	1.55	3.81
68	58.74	0.02	48.51	1.25	1.24	3.05
69	61.90	0.01	47.75	3.58	3.55	8.74
70	71.03	0.01	49.27	6.46	6.41	15.77
71	71.38	0.01	48.76	6.01	5.96	14.67
72	85.78	0.01	51.79	6.55	6.50	15.99
73	92.11	0.01	55.33	6.90	6.84	16.85
74	72.45	0.02	55.84	3.84	3.81	9.37
75	78.76	0.01	61.90	6.55	6.50	15.99
76	61.18	0.01	56.85	6.23	6.18	15.21
77	39.03	0.01	60.63	6.98	6.92	17.04
78	NA	NA	NA	NA	NA	NA
79	51.36	0.02	50.03	2.69	2.67	6.57
80	57.68	0.02	56.35	4.62	4.58	11.28
81	71.05	0.02	67.97	5.03	4.99	12.28
82	74.21	0.02	73.28	7.78	7.72	18.99
83	103.40	0.02	78.83	8.80	8.73	21.48
84	109.05	0.03	79.34	9.03	8.96	22.05

	AW	AX	AY	AZ	BA	BB
1	Sensible	Total	Total	% heat	Total	Closure
2	heat water	energy in	heat	loss	output	
3	condensate	condensate	losses			
4	(MJ/h)	(MJ/h)	(MJ/h)	(%)	(MJ/h)	(%)
5	0.01	2.25	56.48	40.10	165.97	116.69
6	0.02	4.39	81.61	30.78	291.04	108.87
7	0.02	3.93	104.81	24.18	440.20	100.74
8	0.04	4.16	125.98	23.09	545.64	99.29
9	0.03	3.26	143.05	24.46	615.96	104.63
10	0.04	3.95	158.25	22.73	677.41	96.63
11	0.10	7.71	172.54	21.89	786.62	99.23
12	0.21	15.46	191.39	17.76	879.58	81.29
13	0.02	4.88	61.61	36.52	212.49	125.05
14	0.03	5.42	80.33	25.23	335.90	104.90
15	0.05	5.76	105.14	23.73	470.14	105.52
16	0.08	8.91	129.56	23.13	579.24	102.88
17	0.10	10.26	144.64	22.49	662.73	102.47
18	0.09	10.27	158.70	21.48	751.81	101.18
19	0.11	10.88	170.34	20.84	851.61	103.64
20	0.12	11.89	187.88	20.38	929.71	100.38
21	0.17	14.92	206.84	19.23	1031.13	95.47
22	0.03	4.81	65.07	37.35	212.02	121.03
23	0.05	6.27	84.28	24.62	375.02	108.89
24	0.07	7.32	109.53	23.19	483.05	101.75
25	0.08	8.33	131.76	22.74	595.59	102.30
26	0.13	10.43	147.43	21.05	719.75	102.30
27	0.14	12.03	162.31	19.63	876.62	105.54
28	0.13	11.63	178.05	19.42	1003.08	108.86
29	0.19	14.45	200.16	18.80	1105.91	103.41
30	0.24	17.23	224.95	18.10	1056.99	84.75
31	0.04	5.98	71.29	26.72	290.10	108.22
32	0.04	5.85	90.06	23.44	397.99	103.04
33	0.05	6.27	115.74	27.88	482.42	115.54
34	0.06	6.50	138.39	29.17	566.39	118.78
35	0.08	7.74	153.94	26.27	725.25	123.09
36	0.10	10.13	168.34	23.90	821.65	116.05
37	0.15	12.19	188.13	21.78	906.29	104.43
38	0.20	16.88	212.23	19.28	996.41	90.19
39	0.22	18.11	238.65	20.21	1040.72	87.82
40	0.05	7.50	73.70	21.95	383.95	113.75
41	0.08	8.67	97.19	19.85	509.22	103.40
42	0.10	11.11	121.33	20.41	649.72	108.67
43	0.14	15.15	143.00	19.89	797.74	110.37
44	0.14	15.84	157.20	19.05	849.71	102.48
45	0.20	17.29	188.01	16.24	929.96	80.03

	AW	AX	AY	AZ	BA	BB
46	0.21	17.91	228.15	17.94	992.26	77.72
47	0.27	22.00	254.33	18.03	1058.24	74.75
48	NA	NA	NA	NA	NA	NA
49	0.04	5.82	75.41	18.97	376.77	94.13
50	0.05	7.32	95.83	17.95	487.92	90.81
51	0.05	7.43	120.62	19.25	614.57	97.46
52	0.05	7.91	142.78	18.97	742.93	98.02
53	0.08	7.77	159.01	18.42	858.90	98.81
54	0.08	8.43	187.24	19.14	989.77	100.46
55	0.09	8.78	226.82	20.27	1035.51	91.95
56	0.12	9.89	254.68	20.47	1181.43	94.35
57	0.07	8.47	85.14	35.80	278.69	116.48
58	0.04	6.98	102.87	38.94	317.99	119.62
59	0.11	12.27	138.15	23.39	600.59	101.21
60	0.13	11.73	163.79	25.85	667.98	104.95
61	0.25	22.00	195.08	22.86	833.91	97.39
62	0.26	21.60	232.08	27.86	893.27	106.81
63	0.02	2.54	68.74	26.48	283.46	108.29
64	0.02	2.59	68.25	28.85	271.85	113.97
65	NA	NA	NA	NA	NA	NA
66	0.03	2.57	165.37	25.16	611.54	92.37
67	0.04	3.85	206.59	24.85	779.98	93.19
68	0.03	3.08	230.48	25.53	841.69	92.65
69	0.07	8.81	212.76	30.27	674.73	95.55
70	0.11	15.88	167.51	27.21	622.23	100.50
71	0.09	14.76	131.03	26.59	560.07	112.73
72	0.08	16.07	100.77	25.29	484.01	120.23
73	0.08	16.92	76.51	21.14	422.66	115.42
74	0.08	9.45	213.17	30.56	643.97	91.86
75	0.11	16.10	167.96	28.06	581.73	96.60
76	0.09	15.30	130.54	27.30	481.39	99.94
77	0.09	17.13	100.56	23.79	395.40	92.75
78	NA	NA	NA	NA	NA	NA
79	0.07	6.63	88.33	30.54	331.79	113.98
80	0.10	11.38	112.92	25.73	456.06	103.29
81	0.11	12.39	145.35	27.55	565.97	106.60
82	0.17	19.16	177.63	23.12	736.05	95.25
83	0.20	21.68	217.17	24.38	834.11	93.19
84	0.23	22.28	248.59	25.37	1032.55	104.78

APPENDIX VI

Thermal efficiency, energy balance over system and diesel displacement data for runs 22-101

	A	B	C	D	E	F
1	Run	Volume of	Specific	Diesel	Total	Energy
2		diesel	diesel	displacement	energy in	diesel
3		used	consumption		gas	in
4		(l/h)	(l/KWh)	(%)	(MJ/h)	(MJ/h)
5	R22	0.57	0.123	67.10	73.72	21.51
6	R23	1.12	0.120	67.91	143.40	42.42
7	R24	2.04	0.117	68.59	262.80	77.69
8	R25	2.64	0.116	69.09	353.99	100.19
9	R26	2.93	0.114	69.52	398.13	111.37
10	R27	3.19	0.112	70.05	439.86	121.33
11	R28	2.94	0.112	69.92	460.78	111.59
12	R29	2.74	0.115	69.25	462.78	104.03
13	R30	0.69	0.123	67.01	90.12	26.26
14	R31	1.33	0.122	67.30	166.50	50.67
15	R32	1.96	0.121	67.62	250.33	74.57
16	R33	2.53	0.119	68.05	322.12	96.28
17	R34	3.00	0.118	68.45	380.81	113.91
18	R35	3.54	0.115	69.25	470.13	134.63
19	R36	3.74	0.114	69.52	509.08	142.12
20	R37	3.68	0.115	69.25	514.76	139.87
21	R38	3.35	0.118	68.45	552.24	127.37
22	R39	0.69	0.130	65.24	79.73	26.19
23	R40	1.38	0.128	65.79	176.55	52.53
24	R41	1.99	0.125	66.57	240.16	75.56
25	R42	2.58	0.121	67.65	324.29	97.95
26	R43	2.92	0.110	70.59	401.05	110.80
27	R44	3.54	0.116	68.98	509.90	134.48
28	R45	3.90	0.117	68.85	625.94	148.35
29	R46	3.36	0.119	68.18	671.99	127.56
30	R47	2.75	0.121	67.64	564.03	104.41
31	R48	0.79	0.129	65.50	93.48	29.91
32	R49	1.39	0.125	66.57	171.32	52.76
33	R50	1.81	0.122	67.37	220.46	68.64
34	R51	2.08	0.119	68.17	265.36	79.17
35	R52	2.94	0.117	68.71	387.10	111.63
36	R53	3.44	0.113	69.66	449.77	130.69
37	R54	3.38	0.116	68.98	501.71	128.32
38	R55	3.10	0.118	68.45	507.83	117.94
39	R56	2.51	0.121	67.64	508.03	95.21
40	R57	1.08	0.124	66.84	123.29	41.01
41	R58	1.69	0.121	67.65	206.09	64.39
42	R59	2.31	0.118	68.45	297.96	87.92
43	R60	2.93	0.115	69.25	372.47	111.48
44	R61	3.28	0.114	69.52	389.46	124.78
45	R62	2.91	0.116	69.11	407.00	110.64

	A	B	C	D	E	F
46	R63	2.25	0.117	68.72	414.50	85.37
47	R64	1.74	0.121	67.65	445.26	66.21
48	R65	NA	NA	NA	NA	NA
49	R66	1.34	0.122	67.38	177.11	51.01
50	R67	1.94	0.120	67.91	246.03	73.89
51	R68	2.51	0.118	68.45	322.90	95.52
52	R69	2.97	0.115	69.25	408.94	112.77
53	R70	3.06	0.114	69.52	487.48	116.12
54	R71	2.68	0.115	69.25	559.32	101.86
55	R72	2.32	0.117	68.71	534.54	88.07
56	R73	1.69	0.119	68.18	592.64	64.24
57	R74	1.02	0.123	67.11	79.91	38.81
58	R75	0.92	0.114	69.53	100.27	35.08
59	R76	2.70	0.120	67.91	223.61	102.62
60	R77	2.79	0.114	69.52	251.29	106.16
61	R78	3.22	0.120	67.91	290.96	122.24
62	R79	3.05	0.120	67.91	302.41	115.85
63	R80	1.07	0.116	68.99	154.96	40.56
64	R81	1.06	0.115	69.25	142.03	40.21
65	R82	NA	NA	NA	NA	NA
66	R83	2.90	0.112	70.05	380.98	110.26
67	R84	3.01	0.114	69.51	464.66	114.41
68	R85	3.03	0.111	70.32	500.88	115.17
69	R86	2.54	0.118	68.45	343.51	96.43
70	R87	2.49	0.121	67.64	318.54	94.76
71	R88	2.42	0.123	67.11	294.13	92.10
72	R89	2.16	0.125	66.57	229.59	82.21
73	R90	2.13	0.132	64.71	181.79	80.77
74	R91	2.49	0.121	67.64	293.06	94.76
75	R92	2.34	0.124	66.84	257.01	89.09
76	R93	2.27	0.129	65.51	217.52	86.28
77	R94	2.28	0.139	62.83	178.05	86.66
78	R95	NA	NA	NA	NA	NA
79	R96	1.06	0.113	69.79	135.44	40.37
80	R97	1.28	0.112	70.05	217.74	48.54
81	R98	1.98	0.105	71.93	269.21	75.41
82	R99	2.39	0.100	73.26	391.77	90.84
83	R100	2.53	0.096	74.34	413.02	96.32
84	R101	2.99	0.091	75.67	573.29	113.80

	G	H	I	J	K	L
1	Total	Electric	Power	Thermal	Total energy	Total energy
2	energy	power	output	efficiency	wood	diesel + wood
3	in	out	out		in	in
4	(MJ/h)	(KW)	(MJ/h)	(%)	(MJ/h)	(MJ/h)
5	95.23	4.6	16.56	17.39	142.23	163.74
6	185.82	9.3	33.48	18.02	267.33	309.75
7	340.49	17.4	62.64	18.40	436.96	514.65
8	454.18	22.8	82.08	18.07	549.53	649.72
9	509.50	25.7	92.52	18.16	588.72	700.09
10	561.19	28.5	102.60	18.28	701.00	822.33
11	572.37	26.1	93.96	16.42	792.71	904.30
12	566.81	23.8	85.68	15.12	1081.98	1186.01
13	116.38	5.6	20.16	17.32	169.92	196.18
14	217.17	10.9	39.24	18.07	320.19	370.86
15	324.91	16.2	58.32	17.95	445.56	520.13
16	418.40	21.2	76.32	18.24	563.05	659.33
17	494.72	25.4	91.44	18.48	646.76	760.67
18	604.76	30.8	110.88	18.33	743.03	877.66
19	651.20	32.8	118.08	18.13	821.70	963.82
20	654.63	32.0	115.20	17.60	926.21	1066.08
21	679.61	28.4	102.24	15.04	1080.11	1207.48
22	105.92	5.3	19.08	18.01	175.18	201.37
23	229.08	10.8	38.88	16.97	344.36	396.89
24	315.72	15.9	57.24	18.13	474.75	550.31
25	422.24	21.3	76.68	18.16	582.22	680.17
26	511.85	26.5	95.40	18.64	703.55	814.35
27	644.38	30.5	109.80	17.04	830.59	965.07
28	774.29	33.5	120.60	15.58	921.41	1069.76
29	799.55	28.2	101.52	12.70	1069.47	1197.03
30	668.44	22.7	81.72	12.23	1247.15	1351.56
31	123.39	6.1	21.96	17.80	268.06	297.97
32	224.08	11.1	39.96	17.83	386.26	439.02
33	289.10	14.8	53.28	18.43	417.55	486.19
34	344.53	17.5	63.00	18.29	476.83	556.00
35	498.73	25.1	90.36	18.12	589.22	700.85
36	580.46	30.3	109.08	18.79	707.99	838.68
37	630.03	29.1	104.76	16.63	867.79	996.11
38	625.77	26.3	94.68	15.13	1104.84	1222.78
39	603.24	20.7	74.52	12.35	1185.10	1280.31
40	164.30	8.7	31.32	19.06	337.53	378.54
41	270.48	14.0	50.40	18.63	492.45	556.84
42	385.88	19.6	70.56	18.29	597.90	685.82
43	483.95	25.5	91.80	18.97	722.74	834.22
44	514.24	28.8	103.68	20.16	829.13	953.91
45	517.64	25.2	90.72	17.53	1161.96	1272.60

	G	H	I	J	K	L
46	499.87	19.2	69.12	13.83	1276.63	1362.00
47	511.47	14.4	51.84	10.14	1415.63	1481.84
48	NA	NA	NA	NA	NA	NA
49	228.12	11.0	39.60	17.36	400.27	451.28
50	319.92	16.2	58.32	18.23	537.29	611.18
51	418.42	21.3	76.68	18.33	630.61	726.13
52	521.71	25.8	92.88	17.80	757.96	870.73
53	603.60	26.8	96.48	15.98	869.25	985.37
54	661.18	23.3	83.88	12.69	985.24	1087.10
55	622.61	19.8	71.28	11.45	1126.16	1214.23
56	656.88	14.2	51.12	7.78	1252.12	1316.36
57	118.72	8.3	29.88	25.17	239.26	278.07
58	135.35	8.1	29.16	21.54	265.84	300.92
59	326.23	22.5	81.00	24.83	593.39	696.01
60	357.45	24.5	88.20	24.67	636.47	742.63
61	413.20	26.8	96.48	23.35	856.27	978.51
62	418.26	25.4	91.44	21.86	836.33	952.18
63	195.52	9.2	33.12	16.94	261.75	302.31
64	182.24	9.2	33.12	18.17	238.51	278.72
65	NA	NA	NA	NA	NA	NA
66	491.24	25.9	93.24	18.98	662.04	772.30
67	579.07	26.4	95.04	16.41	837.01	951.42
68	616.05	27.3	98.28	15.95	908.47	1023.64
69	439.94	21.5	77.40	17.59	706.12	802.55
70	413.30	20.6	74.16	17.94	619.14	713.90
71	386.23	19.7	70.92	18.36	496.82	588.92
72	311.80	17.3	62.28	19.97	402.55	484.76
73	262.56	16.1	57.96	22.07	366.17	446.94
74	387.82	20.6	74.16	19.12	701.02	795.78
75	346.10	18.9	68.04	19.66	602.18	691.27
76	303.80	17.6	63.36	20.86	481.69	567.97
77	264.71	16.4	59.04	22.30	426.32	512.98
78	NA	NA	NA	NA	NA	NA
79	175.81	9.4	33.84	19.25	291.09	331.46
80	266.28	11.4	41.04	15.41	441.52	490.06
81	344.62	18.9	68.04	19.74	530.95	606.36
82	482.61	23.9	86.04	17.83	772.75	863.59
83	509.34	26.4	95.04	18.66	895.07	991.39
84	687.09	32.9	118.44	17.24	985.38	1099.18

	M	N	O	P	Q	R
1	Total energy	Heat	Total	Total heat	Total	Closure
2	tar,char and	losses	heat	overall heat	energy	
3	condensate	engine	losses	losses	out	
4	(MJ/h)	(MJ/h)	(MJ/h)	(MJ/h)	(MJ/h)	(%)
5	35.78	78.67	56.48	135.15	187.49	**114.50**
6	66.03	152.34	81.61	233.95	333.46	**107.65**
7	72.58	277.85	104.81	382.66	517.88	**100.63**
8	65.67	372.10	125.98	498.08	645.83	**99.40**
9	74.78	416.98	143.05	560.03	727.33	**103.89**
10	79.29	458.59	158.25	616.84	798.73	**97.13**
11	153.30	478.41	172.54	650.95	898.21	**99.33**
12	225.41	481.13	191.39	672.52	983.61	**82.93**
13	60.76	96.22	61.61	157.83	238.75	**121.70**
14	89.07	177.93	80.33	258.26	386.57	**104.24**
15	114.67	266.59	105.14	371.73	544.72	**104.73**
16	127.28	342.08	129.56	471.64	675.24	**102.41**
17	137.28	403.28	144.64	547.92	776.64	**102.10**
18	122.98	493.88	158.70	652.58	886.44	**101.00**
19	172.20	533.12	170.34	703.46	993.74	**103.10**
20	227.07	539.43	187.88	727.31	1069.58	**100.33**
21	272.05	577.37	206.84	784.21	1158.50	**95.94**
22	67.22	86.84	65.07	151.91	238.21	**118.29**
23	114.19	190.20	84.28	274.48	427.55	**107.73**
24	133.36	258.48	109.53	368.01	558.61	**101.51**
25	139.54	345.56	131.76	477.32	693.54	**101.97**
26	171.28	416.45	147.43	563.88	830.56	**101.99**
27	204.41	534.58	162.31	696.89	1011.10	**104.77**
28	199.09	653.69	178.05	831.74	1151.43	**107.63**
29	233.75	698.03	200.16	898.19	1233.46	**103.04**
30	268.01	586.72	224.95	811.67	1161.40	**85.93**
31	125.33	101.43	71.29	172.72	320.01	**107.40**
32	136.60	184.12	90.06	274.18	450.74	**102.67**
33	146.22	235.82	115.74	351.56	551.06	**113.34**
34	162.64	281.53	138.39	419.92	645.56	**116.11**
35	184.20	408.37	153.94	562.31	836.87	**119.41**
36	203.54	471.38	168.34	639.72	952.34	**113.55**
37	216.46	525.27	188.13	713.40	1034.62	**103.87**
38	276.35	531.09	212.23	743.32	1114.35	**91.13**
39	294.07	528.72	238.65	767.37	1135.96	**88.73**
40	186.95	132.98	73.70	206.68	424.95	**112.26**
41	205.94	220.08	97.19	317.27	573.61	**103.01**
42	230.43	315.32	121.33	436.65	737.64	**107.56**
43	282.27	392.15	143.00	535.15	909.22	**108.99**
44	303.05	410.56	157.20	567.76	974.49	**102.16**
45	334.95	426.92	188.01	614.93	1040.60	**81.77**

	M	N	O	P	Q	R
46	349.61	430.75	228.15	658.90	1077.63	**79.12**
47	358.65	459.63	254.33	713.96	1124.45	**75.88**
48	NA	NA	NA	NA	NA	**NA**
49	124.25	188.52	75.41	263.93	427.78	**94.79**
50	146.06	261.60	95.83	357.43	561.81	**91.92**
51	171.05	341.74	120.62	462.36	710.09	**97.79**
52	191.21	428.83	142.78	571.61	855.70	**98.27**
53	212.41	507.12	159.01	666.13	975.02	**98.95**
54	243.21	577.30	187.24	764.54	1091.63	**100.42**
55	274.15	551.33	226.82	778.15	1123.58	**92.53**
56	334.12	605.76	254.68	860.44	1245.68	**94.63**
57	113.64	88.84	85.14	173.98	317.50	**114.18**
58	114.85	106.19	102.87	209.06	353.07	**117.33**
59	238.83	245.23	138.15	383.38	703.21	**101.03**
60	252.90	269.25	163.79	433.04	774.14	**104.24**
61	347.86	316.72	195.08	511.80	956.14	**97.71**
62	358.78	326.82	232.08	558.90	1009.12	**105.98**
63	59.76	162.40	68.74	231.14	324.02	**107.18**
64	61.57	149.12	68.25	217.37	312.06	**111.96**
65	NA	NA	NA	NA	NA	**NA**
66	65.18	398.00	165.37	563.37	721.79	**93.46**
67	108.73	484.03	206.59	690.62	894.39	**94.01**
68	110.34	517.77	230.48	748.25	956.87	**93.48**
69	118.46	362.54	212.76	575.30	771.16	**96.09**
70	136.18	339.14	167.51	506.65	716.99	**100.43**
71	134.90	315.31	131.03	446.34	652.16	**110.74**
72	153.65	249.52	100.77	350.29	566.22	**116.80**
73	164.35	204.60	76.51	281.11	503.42	**112.64**
74	137.74	313.66	213.17	526.83	738.73	**92.83**
75	156.76	278.06	167.51	445.57	670.37	**96.98**
76	133.32	240.44	131.03	371.47	568.15	**100.03**
77	116.79	205.67	100.56	306.23	482.06	**93.97**
78	NA	NA	NA	NA	NA	**NA**
79	108.02	141.97	88.33	230.30	372.16	**112.28**
80	125.40	225.24	112.92	338.16	504.60	**102.97**
81	151.40	276.58	145.35	421.93	641.37	**105.77**
82	166.65	396.57	177.63	574.20	826.89	**95.75**
83	203.92	414.30	217.17	631.47	930.43	**93.85**
84	210.67	568.65	248.59	817.24	1146.35	**104.29**

APPENDIX VII

Heat losses estimation data for runs 22-101

	A	B	C	D	E	F	G
1	Runs	Wall	Heat	Heat	Wall	Heat	Heat
2		temp	radiation	conduction	temp	radiation	conduction
3		zone1	zone1	zone1	zone2	zone2	zone2
4		(K)	(MJ/h)	(MJ/h)	(K)	(MJ/h)	(MJ/h)
5							
6	R22	400	4.17	2.81	453	1.98	1.18
7	R23	473	10.34	5.87	543	4.67	2.18
8	R24	523	16.58	8.18	593	6.88	2.77
9	R25	573	24.95	10.73	643	9.73	3.42
10	R26	598	30.00	11.99	668	11.42	3.73
11	R27	623	35.72	13.25	693	13.30	4.05
12	R28	648	42.17	14.54	700	13.87	4.14
13	R29	673	49.42	15.87	733	16.78	4.57
14	R30	423	5.86	3.83	493	3.02	1.64
15	R31	473	10.39	5.94	543	4.68	2.19
16	R32	523	16.61	8.23	593	6.88	2.78
17	R33	573	24.90	10.64	643	9.72	3.39
18	R34	598	30.01	12.00	668	11.42	3.74
19	R35	623	35.69	13.21	693	13.30	4.04
20	R36	648	42.18	14.57	700	13.87	4.14
21	R37	673	49.42	15.86	733	16.77	4.57
22	R38	698	57.56	17.28	753	18.75	4.85
23	R39	423	5.87	3.84	493	3.02	1.64
24	R40	473	10.39	5.95	543	4.69	2.19
25	R41	523	16.64	8.27	593	6.89	2.79
26	R42	573	24.90	10.64	643	9.72	3.39
27	R43	598	30.05	12.07	668	11.43	3.75
28	R44	623	35.71	13.23	693	13.30	4.04
29	R45	648	42.13	14.47	700	13.86	4.12
30	R46	673	49.45	15.93	733	16.78	4.58
31	R47	693	55.85	16.98	783	22.01	5.25
32	R48	433	6.69	4.30	503	3.32	1.76
33	R49	483	11.50	6.40	553	5.08	2.31
34	R50	533	18.10	8.71	603	7.40	2.90
35	R51	583	26.84	11.13	653	10.37	3.52
36	R52	608	32.20	12.48	678	12.14	3.86
37	R53	633	38.18	13.71	703	14.11	4.16
38	R54	658	45.02	15.15	733	16.79	4.59
39	R55	683	52.57	16.44	783	22.01	5.26
40	R56	708	61.08	17.88	790	22.83	5.37
41	R57	433	6.62	4.20	503	3.31	1.74
42	R58	483	11.51	6.43	553	5.08	2.32
43	R59	533	18.09	8.70	603	7.40	2.90
44	R60	583	26.84	11.13	653	10.37	3.52
45	R61	608	32.14	12.38	678	12.13	3.83
46	R62	643	40.83	14.30	713	14.97	4.31
47	R63	693	55.85	16.98	793	23.18	5.39
48	R64	718	64.68	18.34	803	24.40	5.52
49	R65	NA	NA	NA	NA	NA	NA
50	R66	433	6.62	4.19	503	3.31	1.73
51	R67	483	11.42	6.29	553	5.06	2.28
52	R68	533	18.07	8.66	603	7.39	2.89
53	R69	583	26.80	11.07	653	10.36	3.50
54	R70	608	32.21	12.50	678	12.15	3.86
55	R71	643	40.79	14.24	713	14.96	4.30
56	R72	693	55.82	16.92	793	23.17	5.38

	A	B	C	D	E	F	G
57	R73	718	64.72	18.41	803	24.40	5.54
58	R74	453	8.40	5.08	523	3.96	1.97
59	R75	503	13.80	7.14	573	5.91	2.50
60	R76	553	21.33	9.70	623	8.50	3.16
61	R77	603	31.07	12.20	673	11.77	3.79
62	R78	653	43.55	14.79	723	15.85	4.44
63	R79	703	59.28	17.54	793	23.18	5.39
64	R80	433	6.62	4.20	503	3.31	1.74
65	R81	433	6.62	4.19	503	3.31	1.73
66	R82	NA	NA	NA	NA	NA	NA
67	R83	603	31.08	12.21	673	11.77	3.79
68	R84	683	52.54	16.38	783	22.00	5.24
69	R85	703	59.24	17.46	793	23.17	5.37
70	R86	703	59.29	17.56	793	23.18	5.40
71	R87	653	43.57	14.83	743	17.75	4.71
72	R88	603	31.06	12.19	693	13.30	4.04
73	R89	553	21.32	9.68	643	9.72	3.40
74	R90	503	13.86	7.23	593	6.88	2.77
75	R91	703	59.32	17.61	793	23.19	5.41
76	R92	653	43.58	14.86	743	17.75	4.72
77	R93	603	31.08	12.21	693	13.30	4.05
78	R94	553	21.33	9.69	643	9.72	3.40
79	R95	NA	NA	NA	NA	NA	NA
80	R96	473	10.40	5.96	543	4.69	2.20
81	R97	523	16.62	8.24	593	6.89	2.78
82	R98	573	24.90	10.63	643	9.71	3.39
83	R99	623	35.65	13.13	693	13.29	4.02
84	R100	673	49.38	15.79	743	17.73	4.68
85	R101	703	59.22	17.42	793	23.17	5.36

	H	I	J	K	L	M	N
1	Wall	Heat	Heat	Wall	Heat loss	Heat loss	Wall
2	temp	radiation	conduction	temp	radiation	conduction	temp
3	zone3	zone3	zone3	bottom	bottom	bottom	top
4	(K)	(MJ/h)	(MJ/h)	(K)	(MJ/h)	(MJ/h)	(K)
5							
6	400	3.67	2.48	453	2.34	1.29	323
7	473	9.11	5.17	523	4.44	2.11	323
8	523	14.61	7.21	573	6.55	2.75	323
9	533	15.97	7.72	623	9.30	3.44	323
10	543	17.35	8.13	648	10.94	3.78	323
11	553	18.79	8.54	673	12.79	4.12	323
12	563	20.32	8.95	698	14.84	4.46	323
13	573	21.94	9.38	723	17.14	4.82	323
14	423	5.16	3.37	483	3.14	1.66	323
15	473	9.15	5.23	523	4.45	2.13	323
16	523	14.63	7.25	573	6.55	2.76	323
17	533	15.93	7.64	623	9.29	3.41	323
18	543	17.35	8.15	648	10.94	3.78	323
19	553	18.77	8.51	673	12.78	4.10	323
20	563	20.33	8.98	673	12.78	4.11	323
21	573	21.93	9.37	698	14.84	4.45	323
22	583	23.67	9.86	723	17.14	4.83	323
23	433	5.86	3.74	483	3.14	1.66	323
24	483	10.12	5.63	523	4.45	2.13	323
25	533	15.96	7.71	573	6.56	2.77	323
26	543	17.31	8.07	623	9.29	3.41	323
27	553	18.85	8.64	648	10.95	3.80	323
28	563	20.32	8.96	673	12.78	4.11	323
29	573	21.91	9.33	698	14.84	4.44	323
30	583	23.68	9.87	723	17.14	4.83	323
31	593	25.47	10.28	773	22.50	5.56	323
32	443	6.64	4.16	493	3.45	1.79	323
33	493	11.16	6.04	533	4.82	2.26	323
34	543	17.32	8.10	583	7.05	2.89	323
35	553	18.76	8.49	633	9.93	3.55	323
36	563	20.34	8.98	658	11.65	3.91	323
37	573	21.93	9.36	683	13.58	4.24	323
38	583	23.70	9.90	708	15.74	4.62	323
39	600	26.79	10.60	733	18.13	4.97	323
40	620	30.84	11.57	783	23.71	5.72	323
41	443	6.58	4.07	493	3.44	1.77	323
42	493	11.17	6.06	533	4.83	2.27	323
43	543	17.32	8.09	583	7.05	2.89	323
44	553	18.76	8.49	633	9.93	3.54	323
45	563	20.29	8.90	658	11.64	3.88	323
46	593	25.48	10.31	718	16.66	4.76	323
47	613	29.36	11.19	768	21.92	5.48	323
48	643	35.94	12.55	800	25.86	5.95	323
49	NA	NA	NA	NA	NA	NA	323
50	443	6.57	4.06	493	3.44	1.76	323
51	493	11.09	5.94	533	4.81	2.23	323
52	543	17.30	8.05	583	7.04	2.88	323
53	553	18.73	8.44	633	9.92	3.53	323
54	563	20.35	9.00	658	11.66	3.91	323
55	593	25.45	10.25	718	16.66	4.74	323
56	613	29.33	11.14	768	21.91	5.46	323

	H	I	J	K	L	M	N
57	643	35.97	12.61	800	25.87	5.97	323
58	473	9.16	5.25	503	3.76	1.89	323
59	523	14.55	7.12	553	5.62	2.46	323
60	573	21.96	9.42	603	8.12	3.16	323
61	598	26.41	10.52	653	11.29	3.83	323
62	618	30.39	11.41	703	15.28	4.53	323
63	628	32.54	11.88	753	20.23	5.26	323
64	443	6.58	4.07	493	3.44	1.77	323
65	443	6.57	4.06	493	3.44	1.76	323
66	NA	NA	NA	NA	NA	NA	323
67	598	26.42	10.53	653	11.29	3.84	323
68	600	26.76	10.55	700	15.01	4.48	323
69	628	32.50	11.82	753	20.22	5.24	323
70	628	32.55	11.90	753	20.23	5.27	323
71	578	22.80	9.63	703	15.29	4.54	323
72	528	15.27	7.45	653	11.29	3.83	323
73	478	9.62	5.41	603	8.12	3.15	323
74	428	5.45	3.47	553	5.63	2.49	323
75	628	32.57	11.94	753	20.24	5.28	323
76	578	22.82	9.65	703	15.29	4.55	323
77	528	15.29	7.47	653	11.29	3.84	323
78	478	9.62	5.42	603	8.12	3.16	323
79	NA	NA	NA	NA	NA	NA	323
80	453	7.40	4.48	603	8.12	3.16	323
81	503	12.24	6.43	653	11.29	3.83	323
82	553	18.76	8.49	703	15.28	4.52	323
83	603	27.32	10.65	728	17.62	4.87	323
84	653	38.32	12.96	753	20.22	5.23	323
85	678	44.86	14.14	778	23.09	5.60	323

	O	P	Q	R	S	T
1	Heat loss	Heat loss	Total	Tin	Heat loss	Heat loss
2	radiation	conduction	heat loss	Reactor-	radiation	conduction
3	top	top	reactor	filter	drum	drum
4	(MJ/h)	(MJ/h)	(MJ/h)	(K)	(MJ/h)	(MJ/h)
5						
6	0.12	0.07	**20.12**	461.5	9.3	5.9
7	0.12	0.08	**44.10**	464.4	9.6	6.1
8	0.12	0.08	**65.72**	467.1	9.8	6.2
9	0.14	0.09	**85.47**	470.2	10.2	6.5
10	0.14	0.09	**97.56**	483.9	11.7	7.1
11	0.13	0.09	**110.79**	490.7	12.5	7.4
12	0.13	0.08	**123.50**	494.1	12.9	7.6
13	0.13	0.08	**140.12**	500.2	13.7	7.9
14	0.14	0.09	**27.91**	444.5	7.7	5.2
15	0.13	0.09	**44.38**	453.6	8.5	5.6
16	0.13	0.08	**65.92**	462.8	9.4	6.0
17	0.13	0.08	**85.13**	487.4	12.1	7.2
18	0.14	0.09	**97.62**	493.2	12.9	7.6
19	0.13	0.08	**110.60**	495.3	13.1	7.6
20	0.13	0.09	**121.19**	496.7	13.3	7.7
21	0.12	0.08	**137.42**	500.9	13.8	7.9
22	0.13	0.09	**154.16**	506.2	14.5	8.2
23	0.14	0.09	**29.00**	451.8	8.4	5.6
24	0.13	0.09	**45.77**	463.1	9.5	6.1
25	0.14	0.09	**67.82**	474.2	10.7	6.6
26	0.13	0.08	**86.94**	487.3	12.1	7.2
27	0.15	0.10	**99.79**	491.8	12.7	7.6
28	0.13	0.08	**112.66**	501.4	13.8	8.0
29	0.12	0.07	**125.28**	511.4	15.1	8.4
30	0.13	0.09	**142.48**	522.6	16.8	9.1
31	0.13	0.08	**164.11**	532.3	18.2	9.6
32	0.15	0.10	**32.36**	464.1	9.6	6.2
33	0.13	0.09	**49.80**	470.4	10.2	6.4
34	0.13	0.08	**72.67**	481.9	11.5	7.0
35	0.12	0.08	**92.79**	489.9	12.4	7.3
36	0.13	0.09	**105.78**	496.7	13.3	7.7
37	0.12	0.08	**119.45**	500.5	13.7	7.9
38	0.14	0.09	**135.74**	510.1	15.0	8.5
39	0.13	0.08	**156.97**	520.0	16.4	8.9
40	0.14	0.09	**179.23**	530.2	17.9	9.5
41	0.13	0.08	**31.94**	476.6	10.9	6.7
42	0.14	0.09	**49.90**	494.8	13.1	7.7
43	0.13	0.08	**72.63**	499.0	13.5	7.8
44	0.12	0.08	**92.77**	504.1	14.2	8.1
45	0.12	0.07	**105.38**	510.2	15.0	8.3
46	0.13	0.09	**131.84**	522.4	16.7	9.1
47	0.13	0.08	**169.54**	530.1	17.9	9.4
48	0.12	0.08	**193.46**	535.7	18.7	9.7
49	NA	NA	NA	NA	NA	NA
50	0.13	0.08	**31.89**	488.4	12.2	7.3
51	0.12	0.07	**49.31**	498.5	13.4	7.7
52	0.12	0.08	**72.48**	501.4	13.8	7.9
53	0.11	0.07	**92.53**	507.6	14.6	8.2
54	0.14	0.09	**105.85**	513.4	15.5	8.6
55	0.12	0.08	**131.59**	523.3	16.8	9.0
56	0.12	0.07	**169.31**	528.0	17.5	9.3

	O	P	Q	R	S	T
57	0.13	0.09	**193.72**	535.1	18.6	9.7
58	0.14	0.09	**39.69**	488.6	12.3	7.4
59	0.11	0.06	**59.29**	481.3	11.3	6.8
60	0.13	0.09	**85.57**	506.0	14.5	8.2
61	0.13	0.08	**111.10**	510.8	15.1	8.5
62	0.13	0.08	**140.44**	515.4	15.7	8.7
63	0.13	0.08	**175.52**	520.4	16.4	8.9
64	0.13	0.08	**31.94**	461.4	9.3	6.0
65	0.13	0.08	**31.89**	463.1	9.5	6.0
66	NA	NA	**NA**	NA	NA	NA
67	0.13	0.09	**111.14**	513.6	15.5	8.6
68	0.12	0.08	**153.16**	513.1	15.4	8.5
69	0.12	0.07	**175.20**	517.5	16.0	8.7
70	0.13	0.09	**175.60**	458.4	9.0	5.8
71	0.13	0.08	**133.33**	448.3	8.0	5.4
72	0.13	0.08	**98.64**	448.3	8.0	5.3
73	0.13	0.08	**70.64**	439.9	7.3	5.0
74	0.12	0.08	**47.97**	437.9	7.1	4.8
75	0.14	0.09	**175.79**	458.1	9.0	5.9
76	0.13	0.09	**133.44**	450.9	8.3	5.5
77	0.13	0.09	**98.74**	443.3	7.6	5.1
78	0.13	0.08	**70.68**	439.3	7.2	4.9
79	NA	NA	**NA**	NA	NA	NA
80	0.14	0.09	**46.62**	475.9	10.8	6.7
81	0.13	0.08	**68.54**	483.9	11.7	7.1
82	0.12	0.08	**95.90**	501.5	13.8	7.9
83	0.11	0.07	**126.73**	508.5	14.7	8.2
84	0.11	0.07	**164.51**	512.9	15.3	8.5
85	0.11	0.07	**193.05**	523.0	16.7	9.0

	U	V	W	X	Y	Z
1	Heat loss	Heat loss	Tin	Heat loss	Heat loss	Heat loss
2	radiation	conduction	Box	radiation	conduction	radiation
3	pipe	pipe	filter	box filter	box filter	pipe
4	(MJ/h)	(MJ/h)	(K)	(MJ/h)	(MJ/h)	(MJ/h)
5						
6	2.85	0.33	398.6	5.03	4.55	0.76
7	2.95	0.34	400.2	5.18	4.68	0.79
8	3.04	0.34	403.7	5.46	4.91	0.83
9	1.26	1.28	407.0	5.82	5.26	0.88
10	3.62	0.40	411.7	6.21	5.55	0.94
11	3.86	0.41	414.3	6.42	5.69	0.97
12	3.98	0.42	417.3	6.67	5.85	1.01
13	4.22	0.44	420.0	6.90	6.01	1.05
14	2.38	0.29	397.0	5.00	4.61	0.76
15	2.63	0.31	399.6	5.18	4.74	0.79
16	2.91	0.34	405.6	5.66	5.10	0.86
17	3.73	0.40	407.2	5.77	5.16	0.88
18	3.96	0.42	410.3	6.10	5.48	0.93
19	4.03	0.42	413.7	6.33	5.59	0.96
20	4.09	0.43	415.1	6.49	5.74	0.98
21	4.24	0.44	416.5	6.58	5.77	1.00
22	4.46	0.46	418.6	6.80	5.97	1.03
23	2.59	0.31	399.9	5.24	4.81	0.79
24	2.92	0.34	402.6	5.43	4.94	0.82
25	3.29	0.37	406.2	5.74	5.19	0.87
26	3.73	0.40	408.7	5.90	5.26	0.89
27	3.92	0.42	411.3	6.23	5.64	0.94
28	4.27	0.44	414.1	6.38	5.64	0.97
29	4.66	0.47	418.1	6.69	5.81	1.01
30	5.17	0.50	424.9	7.39	6.40	1.12
31	5.61	0.53	427.8	7.65	6.56	1.16
32	2.97	0.35	401.2	5.39	4.97	0.82
33	3.16	0.36	403.7	5.53	5.02	0.84
34	3.54	0.39	406.1	5.70	5.13	0.86
35	3.82	0.41	409.2	5.93	5.28	0.90
36	4.09	0.43	411.7	6.20	5.53	0.94
37	4.22	0.44	412.7	6.23	5.50	0.94
38	4.64	0.47	414.9	6.50	5.78	0.99
39	5.05	0.50	418.7	6.79	5.95	1.03
40	5.52	0.53	424.1	7.34	6.39	1.11
41	3.36	0.37	405.1	5.62	5.07	0.85
42	4.03	0.43	410.0	6.08	5.46	0.92
43	4.17	0.43	413.1	6.29	5.58	0.95
44	4.37	0.45	414.5	6.39	5.62	0.97
45	4.61	0.46	415.6	6.46	5.65	0.98
46	5.16	0.50	418.6	6.80	5.97	1.03
47	5.51	0.52	421.7	7.07	6.14	1.07
48	5.77	0.54	425.1	7.37	6.34	1.12
49	NA	NA	NA	NA	NA	NA
50	3.77	0.41	402.9	5.43	4.91	0.82
51	4.14	0.43	408.5	5.84	5.16	0.88
52	4.26	0.44	410.7	6.05	5.36	0.92
53	4.50	0.45	414.5	6.34	5.54	0.96
54	4.77	0.48	416.0	6.58	5.83	1.00
55	5.19	0.50	418.5	6.75	5.88	1.02
56	5.40	0.51	421.8	7.03	6.07	1.07

	U	V	W	X	Y	Z
57	5.75	0.54	425.6	7.47	6.46	1.13
58	3.79	0.41	407.7	5.87	5.29	0.89
59	3.49	0.38	411.0	6.01	5.25	0.91
60	4.46	0.46	420.2	6.95	6.08	1.05
61	4.65	0.47	416.5	6.60	5.82	1.00
62	4.84	0.48	419.9	6.89	6.01	1.05
63	5.07	0.50	422.4	7.14	6.20	1.08
64	2.86	0.33	397.7	5.03	4.60	0.76
65	2.92	0.34	395.7	4.86	4.45	0.74
66	NA	NA	NA	NA	NA	NA
67	4.77	0.48	419.9	6.92	6.06	1.05
68	4.74	0.47	419.7	6.85	5.94	1.04
69	4.93	0.48	422.3	7.08	6.09	1.07
70	2.77	0.32	401.0	5.30	4.82	0.80
71	2.48	0.30	396.6	4.94	4.54	0.75
72	2.48	0.30	389.8	4.42	4.09	0.67
73	2.25	0.27	387.0	4.22	3.93	0.64
74	2.18	0.27	384.0	3.96	3.67	0.60
75	2.77	0.33	401.5	5.37	4.91	0.81
76	2.56	0.31	395.8	4.90	4.52	0.74
77	2.34	0.28	390.2	4.46	4.14	0.68
78	2.23	0.27	385.9	4.15	3.87	0.63
79	NA	NA	NA	NA	NA	NA
80	3.34	0.37	404.4	5.59	5.07	0.85
81	3.61	0.39	408.2	5.88	5.28	0.89
82	4.27	0.44	413.7	6.32	5.58	0.96
83	4.54	0.46	415.5	6.44	5.61	0.98
84	4.72	0.47	417.0	6.58	5.71	1.00
85	5.16	0.50	418.8	6.73	5.82	1.02

	AA	AB	AC	AD	AE	AF
1	Heat loss	Tin	Heat loss	Heat loss	Heat loss	Heat loss
2	conduction	filter-	radiation	conduction	radiation	conduction
3	pipe	condenser	pipe	pipe	condenser	condenser
4	(MJ/h)	(K)	(MJ/h)	(MJ/h)	(MJ/h)	(MJ/h)
5						
6	0.91	374.2	0.66	0.81	2.07	2.48
7	0.93	375.4	0.68	0.84	2.13	2.56
8	0.98	378.9	0.73	0.90	2.29	2.73
9	1.05	382.5	0.80	0.99	2.49	3.01
10	1.11	386.6	0.85	1.05	2.67	3.20
11	1.14	388.3	0.87	1.07	2.73	3.25
12	1.17	391.4	0.92	1.11	2.87	3.38
13	1.20	394.6	0.96	1.16	3.01	3.53
14	0.92	372.3	0.66	0.82	2.05	2.51
15	0.95	375.5	0.70	0.87	2.17	2.63
16	1.02	380.6	0.76	0.94	2.38	2.86
17	1.03	382.9	0.79	0.97	2.47	2.94
18	1.09	384.5	0.83	1.02	2.58	3.11
19	1.12	388.8	0.88	1.06	2.74	3.24
20	1.15	390.3	0.90	1.10	2.82	3.35
21	1.15	393.3	0.94	1.13	2.94	3.45
22	1.19	395.4	0.98	1.19	3.07	3.61
23	0.96	376.2	0.71	0.89	2.22	2.71
24	0.99	377.6	0.72	0.90	2.26	2.74
25	1.04	380.1	0.76	0.95	2.38	2.88
26	1.05	383.8	0.80	0.98	2.51	2.98
27	1.13	386.3	0.86	1.07	2.69	3.27
28	1.13	388.5	0.87	1.07	2.73	3.24
29	1.16	392.8	0.93	1.11	2.90	3.38
30	1.28	394.4	0.97	1.17	3.02	3.57
31	1.31	396.8	1.00	1.20	3.12	3.65
32	0.99	376.6	0.72	0.91	2.26	2.78
33	1.00	378.5	0.74	0.92	2.31	2.79
34	1.02	381.0	0.77	0.95	2.40	2.88
35	1.05	385.4	0.82	1.00	2.58	3.05
36	1.10	387.0	0.86	1.05	2.68	3.20
37	1.10	388.5	0.87	1.05	2.71	3.20
38	1.15	389.8	0.90	1.11	2.82	3.37
39	1.19	391.5	0.92	1.12	2.87	3.39
40	1.27	393.3	0.95	1.16	2.98	3.54
41	1.01	380.4	0.76	0.94	2.37	2.85
42	1.09	384.5	0.83	1.02	2.58	3.11
43	1.11	387.4	0.86	1.05	2.68	3.18
44	1.12	390.1	0.89	1.08	2.79	3.28
45	1.13	391.3	0.91	1.09	2.83	3.31
46	1.19	393.0	0.94	1.15	2.95	3.49
47	1.23	393.8	0.95	1.15	2.98	3.49
48	1.26	395.8	0.98	1.18	3.06	3.58
49	NA	NA	NA	NA	NA	NA
50	0.98	379.0	0.74	0.91	2.31	2.77
51	1.03	382.3	0.77	0.94	2.41	2.85
52	1.07	384.6	0.81	0.99	2.54	3.01
53	1.11	387.8	0.85	1.02	2.65	3.11
54	1.16	389.7	0.90	1.10	2.81	3.35
55	1.17	391.1	0.91	1.10	2.84	3.33
56	1.21	392.5	0.92	1.11	2.89	3.38

	AA	AB	AC	AD	AE	AF
57	1.29	394.3	0.97	1.17	3.02	3.56
58	1.06	384.3	0.82	1.01	2.56	3.08
59	1.05	386.9	0.83	0.99	2.59	3.01
60	1.21	393.1	0.95	1.15	2.96	3.50
61	1.16	391.2	0.92	1.11	2.86	3.39
62	1.20	394.3	0.96	1.15	2.99	3.51
63	1.24	394.9	0.97	1.17	3.03	3.56
64	0.92	373.8	0.67	0.83	2.10	2.54
65	0.89	371.7	0.64	0.80	2.00	2.42
66	NA	NA	NA	NA	NA	NA
67	1.21	392.6	0.94	1.14	2.93	3.46
68	1.19	392.0	0.92	1.10	2.87	3.36
69	1.22	394.8	0.96	1.14	2.99	3.48
70	0.96	376.6	0.71	0.88	2.22	2.68
71	0.91	373.2	0.66	0.83	2.07	2.51
72	0.82	368.6	0.60	0.75	1.88	2.28
73	0.78	365.1	0.56	0.70	1.75	2.13
74	0.73	361.7	0.51	0.63	1.59	1.92
75	0.98	375.8	0.71	0.88	2.20	2.69
76	0.90	372.3	0.66	0.82	2.05	2.49
77	0.83	369.1	0.61	0.76	1.91	2.33
78	0.77	364.7	0.56	0.70	1.74	2.12
79	NA	NA	NA	NA	NA	NA
80	1.01	379.9	0.76	0.94	2.37	2.86
81	1.05	384.6	0.82	1.01	2.56	3.06
82	1.11	389.3	0.88	1.07	2.75	3.24
83	1.12	389.1	0.87	1.04	2.71	3.18
84	1.14	392.1	0.91	1.09	2.85	3.32
85	1.16	393.2	0.93	1.11	2.91	3.37

	AG	AH	AI	AJ
1	Tin	Heat loss	Heat loss	Total
2	air-gas	radiation	conduction	heat loss
3	mixer	air-gas	air-gas	system
4	(K)	(MJ/h)	(MJ/h)	(MJ/h)
5				
6	340.1	0.34	0.41	56.48
7	341.4	0.36	0.44	81.61
8	342.8	0.38	0.46	104.81
9	345.7	0.44	0.55	125.98
10	347.8	0.46	0.58	143.05
11	349.5	0.48	0.60	158.25
12	352.4	0.51	0.64	172.54
13	355.4	0.55	0.69	191.39
14	338.7	0.35	0.43	61.61
15	340.7	0.37	0.45	80.33
16	344.7	0.41	0.51	105.14
17	346.4	0.43	0.53	129.56
18	347.3	0.46	0.58	144.64
19	349.2	0.47	0.58	158.70
20	350.3	0.49	0.61	170.34
21	352.9	0.52	0.64	187.88
22	354.2	0.54	0.68	206.84
23	341.8	0.39	0.48	65.07
24	343.6	0.40	0.50	84.28
25	345.0	0.42	0.53	109.53
26	347.8	0.45	0.55	131.76
27	349.1	0.49	0.63	147.43
28	351.1	0.50	0.62	162.31
29	353.2	0.51	0.63	178.05
30	354.4	0.55	0.69	200.16
31	356.8	0.58	0.72	224.95
32	342.2	0.40	0.51	71.29
33	343.5	0.40	0.50	90.06
34	346.0	0.43	0.53	115.74
35	348.7	0.46	0.56	138.39
36	349.0	0.47	0.59	153.94
37	350.5	0.48	0.59	168.34
38	351.4	0.51	0.65	188.13
39	352.5	0.52	0.64	212.23
40	353.1	0.53	0.67	238.65
41	345.4	0.42	0.52	73.70
42	346.7	0.45	0.57	97.19
43	348.1	0.46	0.57	121.33
44	350.2	0.48	0.59	143.00
45	351.6	0.49	0.60	157.20
46	353.4	0.53	0.67	188.01
47	354.2	0.54	0.67	228.15
48	356.3	0.56	0.70	254.33
49	NA	NA	NA	NA
50	345.4	0.42	0.52	75.41
51	346.5	0.42	0.51	95.83
52	347.0	0.43	0.53	120.62
53	347.7	0.43	0.53	142.78
54	350.0	0.49	0.62	159.01
55	351.3	0.49	0.61	187.24
56	352.8	0.51	0.63	226.82

	AG	AH	AI	AJ
57	353.9	0.54	0.68	254.68
58	347.9	0.46	0.58	85.14
59	349.1	0.44	0.53	102.87
60	351.1	0.50	0.63	138.15
61	352.2	0.51	0.64	163.79
62	354.0	0.53	0.66	195.08
63	354.9	0.55	0.69	232.08
64	343.3	0.40	0.49	68.74
65	340.9	0.36	0.44	68.25
66	NA	NA	NA	NA
67	352.5	0.52	0.65	165.37
68	351.5	0.49	0.61	206.59
69	353.6	0.52	0.64	230.48
70	341.8	0.38	0.47	212.76
71	340.2	0.36	0.44	167.51
72	338.9	0.34	0.41	131.03
73	336.0	0.30	0.37	100.77
74	334.0	0.27	0.32	76.51
75	341.4	0.38	0.48	213.17
76	339.1	0.35	0.43	167.96
77	337.9	0.33	0.40	130.54
78	335.6	0.30	0.37	100.56
79	NA	NA	NA	NA
80	346.2	0.44	0.55	88.33
81	347.7	0.45	0.56	112.92
82	350.1	0.48	0.59	145.35
83	349.9	0.46	0.57	177.63
84	352.0	0.49	0.60	217.17
85	353.9	0.52	0.63	248.59

APPENDIX VIII

Heat losses calculations

HEAT LOSSES ESTIMATIONS

A1.0 Heat losses from gasifier H_{Loss}

To estimate the heat losses from the gasifier it is assumed that the main sources of heat losses are radiation and natural convection. The total heat loss is

$$H_{Loss} = \sum_{0}^{i} Q_r + \sum_{0}^{i} Q_c \qquad [A1.1]$$

where,

$\sum_{0}^{i} Q_r$ = Total heat loss by radiation

$\sum_{0}^{i} Q_c$ = Total heat loss by convection

A1.1 Radiation heat losses

The net radiative heat loss per unit area per unit time, transferred from a grey body of emissivity e at the absolute temperature T_i to the surrounding ambient temperature T_r is given by the Stefan-Boltzmann law as (Coulson and Richardson 1977):

$$Q_r = e * s * A * (T_o^4 - T_r^4) \qquad [A1.2]$$

where,

Q_r = total heat loss by radiation to surrounding
e = emissivity of surface
s = Stefan-Boltzmann constant
A = total surface area of heat transfer
T_o = surface temperature of gasifier
T_r = datum temperature

A1.2 Natural convection heat losses

Since the gasifier is at a higher temperature than the surrounding air, natural convection heat transfer is present and the total heat transfer by natural convection is given by the relationship

$$Q_C = H_C * A * (T_o - T_r) \qquad [A1.3]$$

where,

H_C = convection heat transfer coefficient, W/m^2K
A = total surface area of heat transfer, m^2
T_o = surface temperature, K
T_r = reference temperature, K

For streamline flow for horizontal or vertical pipes, H_C is given as (Coulson and Richardson 1977)

$$Hc = 1.18 * [(T_o - T_r)/d]^{1/4} \qquad [A1.4]$$

where, d = diameter of the gasifier, m

By substituting A1.4 into A1.3,

$$Qc = 1.18 * [(T_o - T_r)/d]^{1/4} * A * (T_o - T_r)$$

$$Qc = \frac{1.18 * (T_o - T_r)^{5/4} * A}{d^{1/4}} \qquad [A1.5]$$

A1.3 Heat loss across gasifer H_{Loss}

The gasifier does not have a uniform surface temperature, as there is a temperature profile along the height of the gasifier. The temperature around the wall of the gasifier was not measured in the trials but in order to estimate the heat losses, a temperature distribution divided into various zones was assumed. Based on the bed analysis of the gasifier illustrated in Figure 5.9, the reaction zones is assumed to be 20 cm. The zones below the reaction zone is taken as 74 cm while the zone above the reaction zone is taken as 84 cm. The temperature estimate was based on temperature profile measurements by Susanto (1989) in Indonesia.

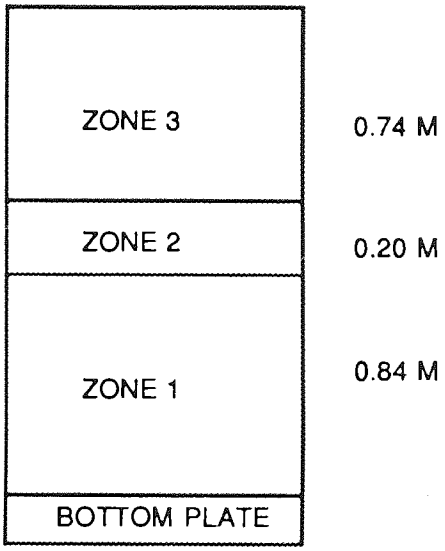


Figure A1.1 Zone division for heat loss estimation

Rearranging equation A1.2 for the i_{th} zone,

$$Q_{r(i)} = e * s * \pi * d * L_i * (T_o^4 - T_r^4) \qquad [A1.6]$$

where,

$Q_{r(i)}$ = total heat transfer in zone i in W
e = emissivity of gasifier wall
s = Stefan-Boltzmann constant = 5.67×10^{-8} W/m^{2}K^4
d = gasifier diameter in m
L_i = height of zone i in m
T_o = surface temperature of gasifier in K
T_r = datum temperature in K

The gasifier was fabricated with rolled ground steel sheets. From Perry et al. 1984, the emissivity of rolled ground steel is 0.55

Similarly, by rearranging equation A1.5,

$$Qc = \frac{1.18 * (T_o - T_r)^{5/4} * \pi * d * L_i}{d^{1/4}}$$

$$= 1.18 * d^{3/4} * (T_o - T_r)^{5/4} * \pi * L_i \qquad [A1.7]$$

The classification of the various zones is illustrated in Figure A1.1 and Table A1.1:

Table A1.1
Gasifier zones selected for heat losses calculations

Gasifier zones (i)	Zone height L_i (m)	Estimated wall zone temperature (K)
1	0.84	573.0
2	0.20	643.0
3	0.74	533.0
4	Bottom plate	623.0
5	Top plate	323.0

Using data from Table A1.1 the heat loss by radiation and convection can be calculated as follows:

A1.3.1 Zone 1

T_o = 573.0 K

T_r = 305.7 K

L_1 = 0.84 m

Substituting the respective values into equation A1.6 ,

$$Qr(1) = 5.67 * 10^{-8} * 0.55 * 3.142 * 0.85 * 0.84 * (573.0^4 - 305.7^4) \text{ W}$$

$$= \frac{5.67*10^{-8}*0.55*3.142*0.85*0.84*(573.0^4-305.7^4)*3600}{10^6} \text{ MJ/h}$$

$$= 24.95 \text{ MJ/h}$$

Substituting the respective values into equation A1.7,

$$Qc(1) = 1.18 * (0.85)^{3/4} * (573-305.7)^{5/4} * 3.142 * 0.84 \text{ W}$$

$$= \frac{1.18 * (0.85)^{3/4} * (573-305.7)^{5/4} * 3.142 * 0.84 * 3600}{10^6} \text{ MJ/h}$$

$$= 10.73 \text{ MJ/h}$$

A1.3.2 Zone 2

Using the same method of calculation as for zone 1, and data from Table A1.1, the heat losses by radiation and convection for zone 2 is summarised as follows:

$Q_r(2)$ = 9.73 MJ/h

$Q_c(2)$ = 3.42 MJ/h

A1.3.3 Zone 3

$Q_r(3)$ = 15.97 MJ/h

$Q_c(3)$ = 7.72 MJ/h

A1.3.4 Bottom plate of reactor

Ti = 623 K

Cross sectional area of bottom plate

$$= \frac{\pi * d^2}{4}$$

where, d = diameter of gasifier

Therefore, A $= \frac{\pi * 0.85 * 0.85}{4} = 0.57\ m^2$

Substituting the respective values in equation 6.43,

$Q_{r(bottom)} = 0.55 * 5.67 * 10^{-8} * 0.57 * (623.0^4 - 305.7^4)$ W

$$= \frac{0.55 * 5.67 * 10^{-8} * 0.57 * (623.0^4 - 305.7^4) * 3600}{10^6} \text{ MJ/h}$$

= 9.30 MJ/h

The thickness of the bottom plate = 0.003 m

Total surface area of bottom plate = 0.58 m^2

Substituting the respective values in equation A1.5,

$$Qc(bottom) = \frac{1.18 * (623.0 - 305.7)^{5/4} * 0.58 * 3600}{0.85^{1/4} * 10^6} \text{ MJ/h}$$

= 34.4 MJ/h

A1.3.5 Top plate of reactor

Using the same method of computation and data from Table A1.1, the heat losses by radiation and convection is summarised as follows:

$Q_{r(top)}$ = 0.14 MJ/h

Qc(top) = 0.09 MJ/h

In summary, the total heat loss by radiation and convection is summarised in Table A2

Table A2
Gasifier heat losses

Gasifier zones	L_i (m)	Q_r (MJ/h)	Q_c (MJ/h)
1	0.84	24.95	10.73
2	0.20	9.73	3.42
3	0.74	15.97	7.72
Bottom plate	-	9.303.44	
Top plate	-	0.14	0.09
Total		60.09	25.40

The total heat loss in equation 6.42 is

H_{Loss} = 60.09 + 25.40 MJ/h = 85.49 MJ/h

Using similar procedure, the heat losses for runs 22-101 are summarised in Appendix VII.

A1.4 Total heat losses to cold clean gas H_{Loss}

The total heat loss is the heat losses from the gasifier and the heat losses across the gas cleaning and cooling system.

A1.4.1 Heat losses across the gasifier

From Table A2, total heat loss from gasifier = 85.49 MJ/h

A1.4.2 Heat losses across the gas cleaning and cooling system

The heat losses are:
Heat losses across drum cooler
Heat losses across box filter
Heat losses across air-cooled condenser
Heat losses of all connecting pipes

Since the surface temperatures were not measured during the experiment, they had to be estimated by taking average temperatures measured in the experiment. The location of the temperature probes is shown in Figure 5.7 and the data is summarised in Appendix III
The estimated surface temperature (See Figure 5.7 and 5.8) is summarised in Table A1.2.

Table A1.2
Estimated surface temperature

Components	Estimated surface temperature K	
Pipe from reactor to drum cooler	$(T_3+T_4)/2$	470.2
Drum cooler	$(T_3+T_4)/2$	470.2
Pipe from drum cooler to box filter	$(T_4+T_5)/2$	407.0
Box filter	$(T_4+T_5)/2$	407.0
Pipe from box filter outlet to air-cooled condenser	$(T_5+T_6)/2$	382.5
Air-cooled condenser	$(T_5+T_6)/2$	382.5
Pipe from air-cooled condenser to air-gas mixer	$(T_6+T_7)/2$	345.7

Heat loss from pipe between reactor outlet and drum cooler

Length of pipe = 1.0 m
Diameter of pipe = 0.0889 m
Total surface area = $\pi * .0889 * 1.0\ m^2 = 0.28\ m^2$
T_o = 470.2 K (See Table A1.2)

Using the same method of computation,
$Q_{r(pipe)}$ = 1.26 MJ/h
$Q_{c(pipe)}$ = 1.28 MJ/h

Heat loss in drum cooler

Height of cooler = 0.9 m
Diameter of cooler = 0.6 m
Total surface area = $\pi * 0.9 * 0.6 + 2 * (\pi * 0.3^2) = 2.27\ m^2$
T_o = 470.2K (See Table A1.2)

Using the same method of computation,
$Q_{r(cooler)}$ = 10.20 MJ/h
$Q_{c(cooler)}$ = 6.50 MJ/h

Heat loss from pipe between drum cooler outlet and box filter

Length of pipe = 1.5 m
Diameter of pipe = 0.0889 m
Total surface area = $\pi * .0889 * 1.5\ m^2 = 0.42\ m^2$
T_o = 407.2 K (See Table A1.2)

Using the same method of computation,
$Q_{r(pipe)}$ = 0.88 MJ/h
$Q_{c(pipe)}$ = 1.05 MJ/h

Box filter

Using the dimensions of the box filter illustrated in Figure 5.5, the total surface area of the box filter is estimated to be:

$= 2(0.457*0.4572+0.4572 * 1.1684+0.4572 * 1.1684) + \pi * 0.2286 * 0.3050$

$= 2.55+0.22\ m^2$

$= 2.77\ m^2$

T_o= 407.0K (See Table A1.2)

Using the same method of computation

Q_r (box filter) = 5.82 MJ/h
Q_c (box filter) = 5.26 MJ/h

Heat loss from pipe connecting box filter and air-cooled condenser

Length of pipe = 2.0 m
Diameter of pipe =0.0889 m
Total surface area = π * .0889 * 2.0 = 0.56 m^2
T_o = 382.5K

Using the same method of computation,
$Q_{r(pipe)}$ = 0.80 MJ/h
$Q_{c(pipe)}$ = 0.99 MJ/h

Air-cooled condenser

Using the dimensions of the air-cooled condenser illustrated in Figure 5.6, the total surface area of the air-cooled condenser is estimated by the following method:

Length of cooler pipe = 1.0 m
Diameter of cooler pipe = 0.038 m

In the air-cooled condenser there were 10 cooler pipes. Hence the total surface area of 10 cooler pipes is

= 10 * π * 0.038 * 1 0
= 1.19 m^2

Using the same method of computation, the total surface area of the air-cooler condenser is 1.75 m^2

From Table A1.2, To = 382.5K

Using the same method of computation,
Q_r (air-cooled condenser) = 2.49 MJ/h
Q_c(air-cooled condenser) = 3.01 MJ/h

Pipe from air-cooled condenser to air-gas mixer

Length of pipe = 2.5 m
Diameter of pipe = 0.0889 m
Total surface area = π * 0.0889 * 2.5 = 0.70 m^2
T_o = 345.7K

Using the same method of computation,
Qr = 0.44 MJ/h
Qc = 0.55 MJ/h

The heat losses can be summarised in Table A1.3

Table A1.3
Summary of estimated heat losses

Components	Estimated heat losses	
	Radiation MJ/h	Convection MJ/h
Pipe from reactor to drum cooler	1.26	1.28
Drum cooler	10.20	6.50
Pipe from drum cooler to box filter	0.88	1.05
Box filter	5.82	5.26
Pipe from box filter outlet to air-cooled condenser	0.80	0.99
Air-cooled condenser	2.49	3.01
Pipe from air-cooled condenser to air-gas mixer	0.44	0.55
Total heat losses	**21.89**	**18.64**

The heat losses of the individual runs are summarised in Appendix VII.

Tctal heat losses from gasifier and gas cooling and cleaning system is therefore

$$H_{Loss} = 85.49+21.68+18.64 \text{ MJ/h}$$
$$= 125.98 \text{ MJ/h}$$

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